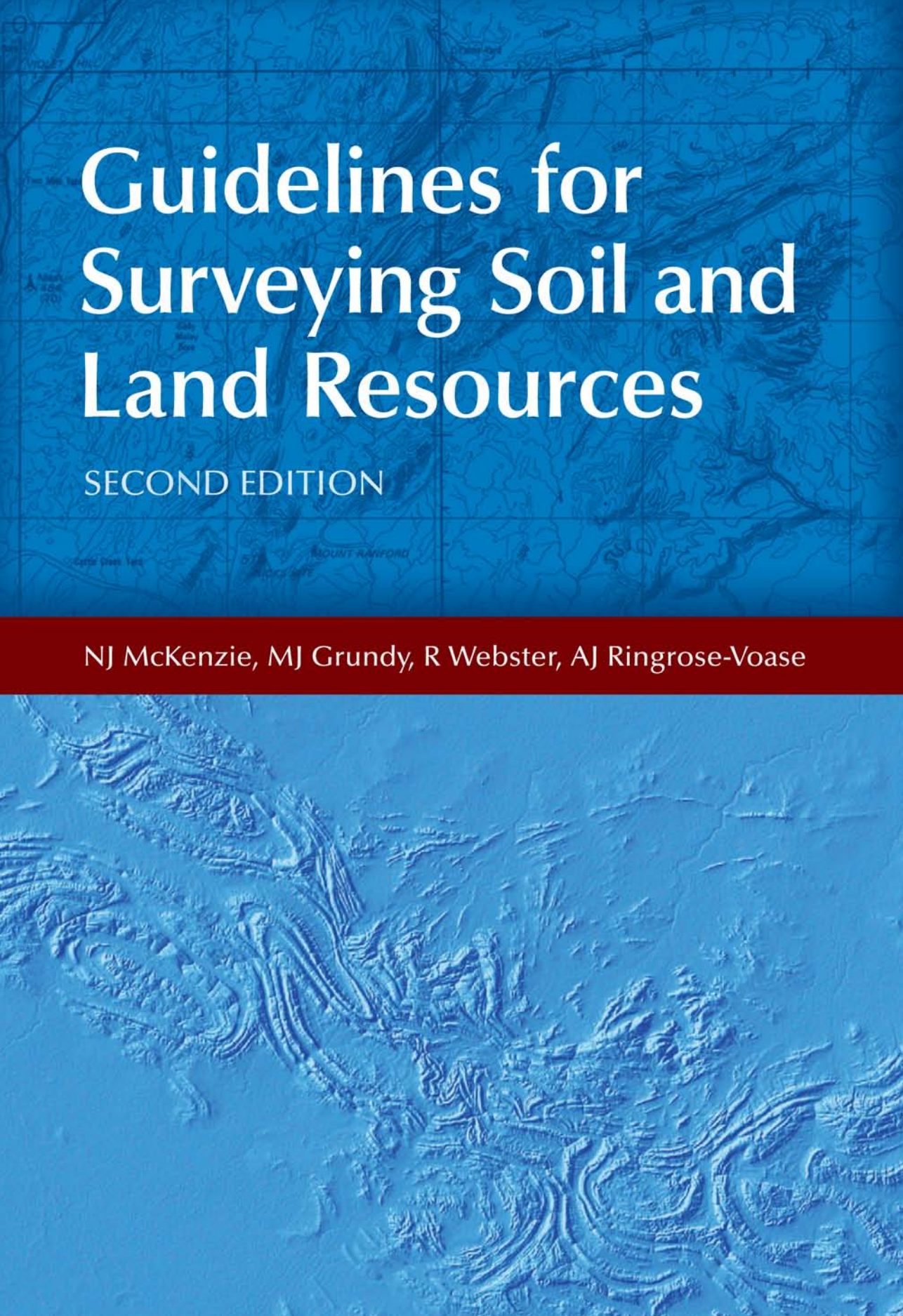


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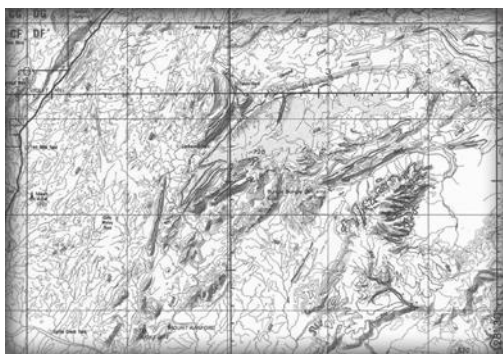
Guidelines for Surveying Soil and Land Resources

SECOND EDITION

NJ McKenzie, MJ Grundy, R Webster, AJ Ringrose-Voase

Guidelines for Surveying Soil and Land Resources

SECOND EDITION



NJ McKenzie

MJ Grundy

R Webster

AJ Ringrose-Voase

Volume 2

Australian Soil and Land Survey Handbook Series



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Part 1

Introduction

Information on soil and land resources is a prerequisite for informed decisions on land use and management. Procedures for acquiring and using this information are introduced and emphasis is given to a balanced approach with elements of mapping, modelling and monitoring within the broader context of environmental change. The conceptual basis for a range of approaches to survey is introduced along with an assessment of strengths and weaknesses. A framework for dealing with scale in measurement and prediction is then introduced.

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Rationale

NJ McKenzie, AJ Ringrose-Voase, MJ Grundy

Introduction

Thousands of decisions are made every day in Australia on how to use land. These range from specific judgements with immediate actions – for example, a farmer deciding to fertilise a paddock or an engineer implementing a plan for residential development – through to more general decisions by government on policy that may ultimately affect every part of the country. Whatever the context, information is needed for sound decisions. Decisions made without the appropriate information leads to inefficient use of resources and environmental degradation.

Decision-making about land use and management requires good information on the characteristics of soil and land, and how they respond to particular treatments. These *Guidelines for surveying soil and land resources* (referred to as the *Guidelines*) help inform you about how to obtain and use the necessary information. Methods for mapping and monitoring soil conditions at a range of scales in space and time are addressed. The rationale behind these *Guidelines* is to promote the development and implementation of consistent methods and standards for surveys of soil and land resources in Australia.

The need for new *Guidelines*

The first edition of the *Guidelines to survey* (Gunn et al. 1988) came at the end of an era in land resource survey. The *integrated survey* method pioneered by Christian and Stewart (1953, 1968) provided the means for mapping land resources in a way that emphasised the connectedness of geology, landform, climate, soil, vegetation, fauna, hydrology and land use. Large areas of Australia were mapped using this method, albeit with variations to suit particular landscapes, land uses and local objectives. In a similar way, soil surveys at more detailed scales were undertaken in many other countries by *free survey*, a method requiring more or less intensive sampling and locally derived systems of soil classification. These methods provided users with *qualitative estimates* of those soil and landscape properties that interested them.

Integrated survey and free survey were, and still are, based on a logic that pre-dated the computer. Observation is predominantly descriptive, and interpretation depends heavily on classification. New and practical methods of land resource survey have emerged since 1985 and they are starting to satisfy a new demand for quantitative information. The advent of geographic information systems (GISs) and databases, global positioning systems, airborne gamma radiometric remote sensing, digital terrain analysis, simulation modelling, statistical analyses, and online access to information have dramatically changed the situation. Experimentation with these technologies has approached a consensus on their best uses, and so it is timely to prepare a new edition of the *Guidelines*.

Readership and structure of the *Guidelines*

These *Guidelines* have been prepared for a broad readership including:

- new surveyors
- more experienced practitioners wishing to update their knowledge
- students and researchers seeking efficient and effective methods for mapping soil and land resources
- people wanting to know how information on soil and land resources is collected and recorded
- commissioners of surveys, funding agencies and those needing guidance on project specifications and expected outcomes from surveys
- allied professionals, particularly in geomorphology, ecology and hydrology, and landscape scientists more generally.

Part 1 of the *Guidelines* introduces the principles of survey and the role of spatial information in the planning and management of natural resources. The main methods of survey are described. The important topic of scale is then addressed because this has a bearing on most aspects of survey practice.

Part 2 addresses landscape context and remote sensing. It begins with an account of geology, landscape development and soil formation. Several environmental attributes (e.g. climate, terrain, aspects of land cover, geophysics) can now be measured or predicted at detailed resolutions across large areas, and this ability has created new opportunities for mapping soil and land resources. Part 2 reviews the technologies along with their use in survey.

Part 3 describes the mechanics of survey from the all-important specification phase, through to practical issues of survey resources, field operations and measurement. Methods for conventional survey and classification are outlined.

Part 4 is concerned with pedometrics¹. Methods are presented for statistical sampling and analysis, digital soil mapping and the characterisation of uncertainty. Principles of information management and synthesis studies conclude the section.

Part 5 covers the use of soil and land information in decision-making, including some aspects of land use planning and soil management. These range from estimating the suitability of land for various land uses through to formulating precise strategies for land management (e.g. irrigation, horticulture, land use planning). The link between survey and monitoring is introduced. Part 5 is both an end and a beginning because soil and land resource information can be used for so many purposes, and only a few can be considered. The *Guidelines* conclude with an overview of the all-pervasive task of communication.

Rationale for land resource assessment

The primary reasons for assessing land resources are to know what resources are present, what the land is good for, and how to manage it to produce food and fibre, to secure water supplies and to conserve valuable assets. Information on land resources gains considerable value when it reduces risks in decision-making. Risks are more readily reduced when the provision of information is closely linked to, and preferably driven by, the decision-making process, whether at the scale of the paddock, enterprise, small catchment, region or country. Many groups of people profitably use information on land resources already, and many more would benefit if they could obtain it in an understandable form.

¹ The application of mathematical and statistical methods for the study of the distribution and genesis of soils.

Reliable information on natural resources is needed, for example, for policy by federal, state, territory and regional agencies because of the emergence of large-scale environmental problems, including climate change, dryland salinity and soil acidification. In particular, improved information is required to:

- assess the effectiveness of, and to better target, major programs in resource management (e.g. Landcare, revegetation, catchment management)
- implement trading schemes (e.g. for salt, water, carbon) to achieve better outcomes
- establish baselines (e.g. for contaminants)
- set targets and to monitor trends.

Information on natural resources is also needed to support a broad range of land use planning and environmental regulatory activities within local, state and territory governments.

In the private sector, industries that depend on natural resources require information to:

- optimise the matching of land use and management with land suitability (some agricultural sectors, most notably viticulture and industrial-scale farm forestry, have increased investment in land resource assessment in recent years)
- implement environmental management systems to comply with duty-of-care regulations and industry codes
- gain market advantage by demonstrating the benign nature of production systems (e.g. green labelling)
- optimise the use of inputs (e.g. nutrient testing to guide fertiliser rates) at the level of the paddock or finer (e.g. variable-rate application of fertiliser in precision agriculture).

Regional communities require better natural resource information to:

- assess and improve the efficacy of land management and target community action (e.g. remedial tree-planting, fencing, weed control, better practices for cropping and grazing)
- improve 'land literacy'².

Surveys also increase our understanding of landscape processes. Although few surveys are undertaken solely for this purpose, much of the understanding of soil development and landscape evolution in Australia has been gained through such studies. Information from land resource survey is fundamental to a broad range of scientific pursuits in disciplines including ecology, hydrology, geomorphology, agronomy and soil science. This information is used to:

- provide a basis for extending research results from well-studied locations to broader areas
- improve understanding of natural processes (e.g. to establish baselines, detect significant deviations, identify cause and effect)
- improve models for explanation and prediction (e.g. better computer models to assess the environmental impact of farming systems)
- improve systems of land use and management
- provide a scientific basis for improved policies in natural resource management.

Mapping, modelling and monitoring as complementary activities

Survey provides only one component of the biophysical information necessary for managing natural resources (Figure 1.1). Survey programs need to be considered along with the

² The ability to read and appreciate the signs of health in a landscape (White 1992).

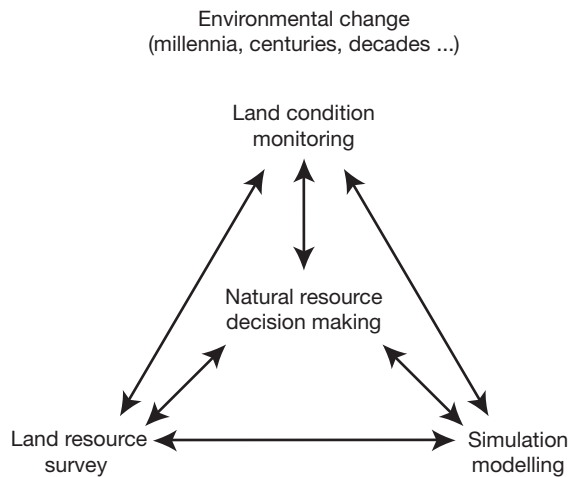


Figure 1.1 Mapping, monitoring and modelling are complementary activities for natural resource management, and they must be set against the context of the sequence of events and processes for a given landscape.

mutually beneficial activities of monitoring and modelling, and all three should then be set within the context of environmental change (Table 1.1). In isolation, each activity can fail to provide the information needed for land management and planning. In combination, they are synergistic and provide a means for improving the quality of land management in Australia. Through integration of these activities, both public agencies and industry are able to maximise the benefits from information gathering and interpretation. This requires an ability to bring together a range of technical specialists: soil surveyors, geomorphologists, computer scientists, mathematicians, field experimentalists, agronomists, foresters and hydrologists.

Table 1.1 Complementary benefits of mapping, monitoring and modelling

Complementary relationship	Benefits
Mapping → monitoring	• Spatial framework for selecting representative sites • System for spatial extrapolation of monitoring results • Broad assessment of resource condition
Monitoring → mapping	• Quantifies and defines important resource variables for mapping • Assesses land suitability over time (including risk assessments for recommended land management)
Modelling → monitoring	• Determines whether trends in specific land attributes can be successfully detected with monitoring • Identifies key components of system behaviour that can be measured in a monitoring program
Monitoring → modelling	• Validates model results • Provides data for modelling
Modelling → Mapping	• Allows spatial and temporal prediction of landscape processes
Mapping → modelling	• Provides data for modelling • Provides spatial association of input variables

The essential context: environmental change

Conceptual models and narratives of environmental change have been developed at the global, continental, regional and, in some instances, local scales. The time spans for these models range from years to decades to millions of years. Past geological, geomorphic, atmospheric, oceanic and ecological events affect current and future landscape processes. For example, they provide natural baselines (e.g. rates of erosion and deposition in different geomorphic settings), insights into potential impacts of climate change and extreme events (e.g. floods, droughts), and an understanding of groundwater behaviour, salt movement and population dynamics (Williams et al. 1998).

The Paleogene and Neogene subperiods (65–1.8 million years ago, mya) and the Pleistocene and Holocene epochs (1.8 mya to the present) are of particular importance because processes during those periods shaped the current landscape. More recently, Aborigines and Europeans have had an impact. Knowledge of environmental change can be used to improve survey quality (see *Chapter 5*). Natural resource decision-makers need to keep in mind the historical aspects of environmental change because it sets the context for current land management.

Mapping

Mapping land resources provides basic information on landscape attributes. Mapping is essential for sound planning and management at all scales. It also provides a framework for determining condition (e.g. degree of degradation) but this requires particular care during the design of the field program. Mapping activities also provide input data to computer models (either through maps or direct measurements at sites) for predicting likely changes in condition under various land uses. Deficiencies exist in the current map cover of Australia:

- maps of land resources in the agricultural areas are incomplete and in most areas the scale is too coarse to be useful for decisions at the primary management level (usually the farm)
- incompatible methods of survey have been used by different agencies, so that national and regional summaries of land resources are difficult to collate
- many of the soil and land attributes that control land degradation and productivity are not measured rigorously and this limits the capacity to improve planning and management
- statistical methods have not been used, and reliable estimates of current conditions may not exist
- because of their broad scale, mapping units often contain a wide range of soil types and are, thus, not effective for stratifying some landscapes to support land use planning and management.

In the mid-term (10–15 years), there are good reasons for Australia to aim to complete a land resource survey coverage at nominal cartographic scales of 1:50 000 for intensively used lands, 1:100 000 for agricultural areas (arable cropping and pasture) and 1:250 000 for the extensive pastoral regions (McKenzie 1991). Obtaining this coverage will require a modest but long-term investment in survey (i.e. similar to the investment from 1990 to 2000). Permanent resource assessment teams are required to ensure continuity of staff and continual improvement of natural resource databases. There is also a need to develop better links between public and private sector surveys. These *Guidelines* provide the methodological framework to assemble country-wide information.

Modelling

Computer modelling of farming systems, forest growth and landscape processes (e.g. erosion, soil acidification, hydrology) can explain and predict changes in resource condition under a wide range of management systems. The results materially assist decision-makers because the forecasts can be expressed in terms of probabilities of occurrence. Computer models are also valuable for exploring potential changes in land condition that are impractical to detect with other methods. For example, variations in climate might mask subtle but important changes in land condition, and detection of a statistically significant change through field measurement might be possible only over an impractically long period (i.e. 50 years or more).

Fully realising the potential benefit of computer models requires:

- appropriate data for running and validating models (with known accuracy and precision)
- research (including field experimentation) to develop better and more integrated computer models useful for guiding land management.

The application of computer modelling to land resource assessment is considered in *Chapter 28*.

Monitoring

Monitoring usually involves:

- establishing baselines for components of ecosystems
- detecting change over time, particularly deviations from natural variation.

Some aspects of monitoring can be addressed through surveys but special-purpose programs of measurement are needed as well. Monitoring is considered in detail in *Chapter 30*.

The trend to quantification

Demand for more reliable information on land resources is increasing. A key requirement is for surveys to provide predictions of clearly defined attributes that control landscape processes (e.g. movement of water, solute, and sediment), and to give explicit statements on the uncertainty of each prediction.

The trend to quantification is a result of several factors.

- The frontier phase of extensive land development in Australia has run its course in most regions. Land resource survey, particularly from the 1920s to the 1980s, focused largely on identifying prime land for agricultural development. Broad-scale qualitative surveys were adequate for the purpose, and detailed soil surveys were undertaken only where irrigation was envisaged. The demand for such qualitative surveys has since waned.
- There are still programs of land development over large areas, but much better information is needed to assess economic returns and environmental outcomes. For example, industrial farm-forestry is expanding in landscapes with suitable combinations of climate and soil, and where trade-offs must be made between forest productivity and water security (e.g. Zhang et al. 2003). Trial and error (see *Informal trial and error*) is not acceptable because the cost of plantation failure is large and water is scarce.
- Some cavalier and ill-informed practices of land use have caused widespread damage to the environment and led to increased regulation and systems for better management. This creates a demand for information on the performances of various forms of land

management on specified tracts of land, along with an assessment of possible impacts. This demands accuracy and precision in mapping, as well as a good understanding of landscape processes and their interactions with land management.

Approaches to land resource assessment

The several approaches to land resource assessment can be ordered according to the degree to which they rely on scientific principles. The least scientific relies on informal trial and error, and has no formal way of organising the experience gained to benefit other land users. Purely empirical methods are better (see *Chapter 18*). More scientific methods are based on models of natural processes with varying levels of complexity. The following account draws heavily on Nix (1968), Basinski (1985) and McKenzie (1991).

Informal trial and error

This form of land resource assessment is the oldest and still the most widely used. Most systems of land use in Australia were established by informal trial and error. However, the economic, social and environmental costs were large. A deficiency with informal trial and error is that experience is inadequately recorded and the prospects for developing rational strategies of land use are limited – particularly when new areas are developed, untried land uses are attempted or lessons once learnt are forgotten when land managers change.

Land resource survey is employed, but on an *ad hoc* basis, usually to identify problems after they have developed. Trial and error can be used to good effect in a more formal and structured approach. For example, field experiments are often a well-organised and efficient means for trial and error (e.g. variety trials for field crops).

Empirical land resource assessment relying on transfer by analogy

Most programs of land resource assessment rely on transfer by analogy. This approach recognises that the results of a land use trial (e.g. farmer's experience, field experimental results, small-catchment study) are strictly applicable to that site only. To seek generality, results are transferred by analogy on the assumption that all occurrences of a particular class of land (i.e. the land analogue) will respond similarly under the same use. The success of the approach relies heavily on the classification and identification of land analogues. These analogues may be defined with classification systems for land (e.g. land system, soil landscape, capability class) or soil (e.g. class of a local or national system such as Isbell (2002)).

Transfer by analogy works well when the criteria used for defining and partitioning land analogues can be readily mapped and are correlated with attributes influencing land use. Most mapping programs that employ the analogy approach depend heavily on morphological descriptions for defining soil and land units. Unfortunately, relationships between soil morphology and other more relevant soil properties are complex and sometimes poor (see *Chapters 3 and 17*).

Semi-empirical land resource assessment

It is widely agreed in Australia that soil taxa from national classifications are unreliable for assessing land resources (Butler 1980). As a result, most survey agencies assess the potential for a nominated land use using individual soil and land characteristics or qualities. Map units have estimates for each soil and land characteristic or quality (the dominant soil taxa are also recorded but just as another attribute of the unit). The assessment of land suitability is usually based on the most limiting characteristic or quality. The major challenge is to obtain reliable estimates of the relevant soil properties (e.g. available water capacity, erodibility, permeability – see *Chapters 17 and 22*).

Land resource assessment using process models

The best theoretical approach to land resource assessment combines mapping with computer models so that dynamic processes can be simulated. However, its practical superiority is only just starting to be evident in routine land resource assessment, despite its being advocated for many years (e.g. Nix 1968, 1981). In process modelling, land performance (expressed in terms of productivity, hazard of use, or management inputs required) is related to individual soil and land characteristics or qualities, and their net effect is assessed by a model of land function. These models may portray specific processes such as water movement (e.g. Verburg et al. 1997) or they may be more comprehensive and model particular farming systems (e.g. Littleboy et al. 1989; Moore et al. 1997; Keating et al. 2003).

Process modelling recognises the complex relationships between land characteristics and utilisation and attempts to represent these explicitly. Conventional approaches to land resource assessment tend to be static, and the implicit model that relates land qualities to land performance is commonly stated qualitatively. In contrast, process modelling allows land resource assessment to be quantitative, dynamic and probabilistic. In particular, interactions between soil and climate can be more fully appreciated.

Process modelling requires measurements at scales appropriate to the process of interest. Many contemporary problems of natural resource management also require predictions at a range of scales (e.g. plot, paddock, farm, small catchment, region).

Opportunities offered by new technology

A goal for land resource survey is to provide predictions of individual soil and land attributes at the required resolution, accuracy and precision in both space and time. This was clearly articulated 40 years ago by Gibbons (1961) and Butler (1963) for example, but the technology to achieve it then was not available. The technological situation has changed, particularly in relation to improved environmental data, measurement, data analysis and communication.

Until recently, environmental data for conventional survey came largely from aerial photography and geological maps. These enabled observations at points to be extended to areas. Reflectance-based remote sensing from satellites (see *Chapter 11*) was used for land resource survey in the 1970s (e.g. Laut et al. 1977) but it did not completely fulfil its promise. New airborne geophysical remote sensing has made a much greater impact by directly sensing soil materials (see *Chapter 13*). These developments, combined with digital terrain analysis (see *Chapter 6*) and continent-wide climate surfaces (see *Chapter 7*), have provided surveyors with much better methods for characterising the environment and soil. These data have been adopted rapidly by survey agencies.

The adoption of new technology for improved soil measurement has not proceeded at the same pace despite the revolution in environmental sensing and measurement. Measurement is now receiving considerable attention as a result of demands from precision agriculture and from contamination and remediation investigations. Some of these techniques are in their infancy. Others are well-instrumented but have few agreed procedures for data analysis and interpretation. Several of the most promising techniques for rapid measurement in the field are based on spectral reflectance imagery or imaging spectroscopy of soil specimens (see *Chapters 11 and 17*). Land resource survey is constrained by the almost total dependence on soil morphology – progress depends on the development of efficient methods for measuring properties that control soil function (e.g. permeability, water storage, nutrient supply).

Electronic databases and GISs have changed land resource assessment practices dramatically since the mid-1980s. Initially they simply followed conventional practice – they were the digital equivalents of filing cabinets and cartography. GISs have powerful facilities, however,

for analysis, combining data, modelling and display. These developments are forcing the reappraisal of older methods, as noted at the beginning of this chapter.

Finally, the integration of GISs and databases with Internet-based software has created new ways for communicating information. Digital products have replaced paper maps, and customised information can be provided on demand (see *Chapter 32*). This change is also forcing us to reappraise survey methods. Survey methods need to move from a project-based mode where a survey is completed, published and then reviewed after 25 years, to a more adaptive system where information is gathered as it is needed and then added to the online digital information system.

Towards a synthesis

Bridging the gap between conventional and quantitative methods

These *Guidelines* have been prepared against a background of greater interaction between field practitioners, with their conventional methods of survey, and pedometricians with their quantitative and sophisticated statistical methods for sampling and prediction (Lagacherie et al. 2006). A synthesis of conventional and quantitative methods is not only possible but essential to support improved management of natural resources. The best aspects of conventional practice provide the following:

- measurements and interpretations cognisant of landscape processes
- mapping and prediction that takes advantage of many lines of evidence beyond the immediate measurement program within a survey
- an integrated view of land resources and their potential use
- a pragmatic approach to field and laboratory studies.

The best aspects of quantitative practice provide:

- transparent and rigorous methods for sampling, measurement and prediction
- estimates of uncertainty for all predictions
- a logical framework for integrating mapping with computer modelling and monitoring.

These *Guidelines* present options for assessing land resources and promote, wherever possible, a synthesis of conventional and quantitative practice.

The changing role of biophysical specialists

An assessment of land resources has long been depicted as an essential precursor to the establishment of 'rational' systems of land use. Its role has been (Gibbons 1976) to assess land for specified purposes either through the hazard of use (e.g. erosion, salinity), potential production (e.g. crop yield, water yield, ecosystem services) or level of management required (e.g. fertiliser additions, soil conservation practices). Practitioners have viewed land resource assessment as the logical first step when land use change is envisaged, whether it is for agricultural development, urban expansion, rehabilitation of degraded lands, or other purposes. Internationally, and to a lesser extent in Australia, land resource assessment has emphasised the soil resource, often with an agricultural leaning.

Although there is no doubt that the physical resources of soil, water, nutrients and energy need to be sufficient for a nominated land use, the limiting factors in any given situation may not always be determined simply by biophysical site factors (Burrough 1996).

In these *Guidelines*, land resource assessment is viewed as just one, albeit important, input to the continuous process of land use change. By definition, the process is interdisciplinary

and can range from formal studies at various scales by large teams of experts to community-based activities that identify potential changes in land use for a local area. The land resource specialist will still provide a scientific view on the potential use of land, but as a contributor to participative social learning.

These *Guidelines* have been prepared when the role of the biophysical specialist is changing. In Australia, natural resource management by public agencies is becoming more local and regional, and an ever-broadening range of users is accessing land resource information. There is no place for the land resource expert to simply impart their views to obedient audiences. Instead, surveyors must participate in a more demanding social process. They, with their emphasis on soil science and geomorphology, have to be members of teams of biophysical specialists who together inform natural resource managers. In some instances, soil and landscape processes will be paramount, whereas in others, ecological or hydrological considerations will dominate. These contributions will always be directed by, and immersed within, the broader social and economic context.

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Approaches to land resource survey

NJ McKenzie, MJ Grundy

Introduction

This chapter provides an overview of the different methods of land resource survey used in Australia. A basic distinction is drawn between qualitative and quantitative methods. Many of the concepts underlying qualitative methods reflect the necessity at the time they were devised for manual methods of data analysis. Widespread access to digital technology has made quantitative approaches a real possibility for many survey organisations. This is forcing a reevaluation of all aspects of land resource survey and these *Guidelines* are a part of that process.

The landscape continuum

Land resource survey is primarily a way of documenting the landscape continuum (Figure 2.1, Plate 1, p. 419). The degree to which this includes vegetation, fauna, groundwater and deeper zones within the regolith¹ varies from study to study. In recent decades the trend has been for land resource surveys in Australia to focus on soil and landform attributes of predominantly cleared landscapes.

Soil is a three-dimensional mantle with varying degrees of internal organisation: lateral, vertical and through time. The mantle material can be characterised by morphological, physical, chemical, mineralogical and biological variables. The degree to which these variables correlate with each other is expressed in the concept of *orderliness* (Butler 1980). Conventional methods of land resource survey work well when a region has a soil mantle with highly correlated variables and zones exist where rapid change occurs over short distances. Unfortunately, the complexity of landscape development in many parts of Australia makes this the exception rather than the rule. Many soils bear the imprint of several different environments (see *Chapter 5*) and unusual combinations of soil properties occur (e.g. formerly leached profiles with subsequent inputs of carbonate; acid soils in arid lands).

Description of the landscape continuum is the core of land resource assessment. Most systems for describing the continuum do so by segmenting it into units that can be described or measured in the field and subsequently represented on maps.

Many systems of nomenclature have arisen during segmentation of the landscape continuum. In Australia, the influence of Northcote (1979), McDonald et al. (1984, 1990), Gunn et al. (1988) and Isbell (1996) has established the following conventions.

¹ The terms *soil* and *regolith* are used interchangeably in this book. In practice, the terms often reflect the training of the worker. *Soil* is used in this book to include all layers that show some degree of pedological organisation (see Isbell 1996, p 7).

- Soil horizons are designated by a master horizon and suffixes are used to provide information on selected aspects (McDonald and Isbell 1990, pp. 108–110). For example, a B2g is a B2 horizon with strong gleying while an A2e horizon is a conspicuously bleached A2.
- The soil profile is the most commonly used unit for describing soil in classification and survey, although there are exceptions in some states (see *Stratigraphic survey*).
- Most map units are defined using physiographic criteria. The units often correspond closely to landform classes at the level of the landform element and landform pattern (Speight 1990).

The conceptual units implied by these conventions are not universally accepted and some countries use fundamentally different schemes (e.g. Baize 1998). There is a long-standing debate over the validity and logic of conceptual units. Much of the debate relates to the genetic implications of some concepts. This issue is most evident in the tension between the use of horizons and profiles as the basic unit for study. Another debate relates to the depiction of spatial variation as being discontinuous when continuous variation is widespread.

Horizons versus profiles

Defining horizons

Soil layers (horizons) are widely accepted as the basic unit of study in land resource survey. Variation between operators can be substantial despite the existence of well-established guidelines (i.e. McDonald et al. 1990). The convention of designating master horizons with the letters A, B, C and so forth was originally just a labelling system (Bridges 1997) but it acquired genetic connotations with the publication of manuals such as that of the Soil Survey Staff (1951). For example, B horizons were described as ‘horizons of illuviation (of accumulation of suspended material from A) or of maximum clay accumulation, or of block or prismatic structure, or both’ (Soil Survey Staff 1951, p. 175). In subsequent decades, the labelling gradually acquired a more comprehensive classificatory role with the use of subscripts to denote particular features. A further development was the introduction of diagnostic horizons to support soil classification (e.g. Soil Survey Staff 1975, 1999; Isbell 1996, 2002; Driessen et al. 2001). Diagnostic horizons define materials more specifically: examples from Isbell (2002) include argic, ferric, manganic, melanic and tenic horizons. Diagnostic horizons, as defined by Northcote (1979), Soil Survey Staff (1999) and Isbell (2002), include criteria relating to layers above and below so they include reference to the soil profile more generally. These diagnostic horizons are not necessarily mutually exclusive and they do not span the full range of soil materials encountered in the field.

Several systems for horizon classification have been developed that aim to be comprehensive. The most ambitious are those of FitzPatrick (1971, 1980, 1988) and Baize (1998). In both approaches, a conceptual gallery of horizon types is defined. The former system has some 80 horizon classes, while the latter has 102 with numerous qualifiers. These horizons are defined in terms of the materials of the horizons alone (i.e. without genetic inference or reference to the profile). A related scheme for defining functional horizons has been devised by the Dutch for practical land evaluation (Wösten et al. 1985; Bouma 1989). In this system, pedologically defined horizons are grouped into fewer horizons that exhibit similar soil hydraulic properties.

The intention with each of these horizon classification systems is to use the horizon classes to generate a great variety of sequences of horizons – they act as building blocks for profiles. More sophisticated quantitative systems using fuzzy classification of horizons have similar objectives (McBratney and de Gruijter 1992). An advantage of horizon-based systems is that a manageable number of classes can be used to describe a much larger suite of profile classes (McBratney 1993).

Implied genesis

The systems for defining horizons and classifying soils in Australia have genetic connotations but these have become less apparent in recent years. Pedologists have wanted to avoid connotations of genesis. For example, McDonald and Isbell (1990, p. 104) state, in relation to horizon designation, that emphasis is on: 'factual objective notation rather than assumed genesis as genetic implications are often uncertain and difficult to establish'. Likewise, one of the guiding principles for the Australian Soil Classification was 'grouping of soils into classes should be based on similarity of soil properties rather than presumed genesis' (Isbell et al. 1997).

The use of genetic criteria for classification and prediction would probably confer many advantages if genesis could be reliably determined (see *Chapter 5*). This is clearly not the case as demonstrated by the protracted debates over soil features such as texture-contrast profiles (Chittleborough 1992; Paton et al. 1995; Phillips 2004) and ferricrete (e.g. Bourman 1993; Pate et al. 2001).

Soil profiles and classification

The concept of the soil profile is strongly entrenched in land resource survey in Australia, and the few attempts to replace it have been only partly successful. Most land resource surveys describe characteristic sequences of horizons according to McDonald et al. (1990) and these are the basic entities for mapping and description. Higher-level classification systems, either local or national, recognise characteristic sequences and group them into hierarchical schemes.

Excellent reviews of profile classification for land resource survey are provided by Mulcahy and Humphries (1967), Avery (1969), Butler (1980), Moore et al. (1983) and see *Chapter 19*. In contrast to horizon-based systems for segmenting the soil continuum, most profile classification schemes are organised hierarchically and allocation of a soil individual to a class is performed using a key. Unlike biological organisms, profiles do not have genes to control them; instead, they are the product of a series of interacting processes operating at different temporal and spatial scales. There is no reason, therefore, to expect a natural hierarchical structure in soil data (Crowther 1953). There are several consequences:

- there is no obvious order of attributes on which to construct a classification scheme
- taxa that are very similar at the lowest level of the scheme may be grouped into different higher order units and placed in separate classes at the highest level
- as profiles are grouped into larger and more inclusive classes (e.g. Soil Orders), the statements that can be made about the taxonomic unit become progressively fewer (Orvedal and Edwards 1941).

An unfortunate consequence of the focus on the A and B horizons in profile classification systems has been limited attention to lower horizons. Although some workers have emphasised subsolum features (e.g. van Dijk 1969), it has been only in recent years that a more complete characterisation of the regolith has been undertaken. This has resulted from several factors:

- regolith and landform evolution studies have become an important part of mineral exploration (Taylor and Eggleton 2001, see *Chapter 4*)
- various applications require soil characterisation to depth (e.g. suitability for deep-rooted perennials and plantation forestry)
- many problems in management require an understanding of the complete regolith and groundwater system (e.g. salinity investigations).

Boundaries between spatial units

Boundaries between spatial units can be defined at different levels of resolution. Unless there is a high level of orderliness, soil and landscape properties will not vary together so locating a boundary involves inevitable compromise. It would be logical to use criteria for boundary placement that relate to the purpose of the survey. For example, boundaries should coincide with critical limits that determine the suitability for different forms of land use. This is often difficult to achieve in practice and, as a result, much mapping is based on readily observed landscape changes.

Soil variation between units may be abrupt or gradual. Qualitative methods of land resource survey do have some facilities for representing such variation. For example, concepts such as the catena and toposequence are used to describe gradual variation within a broader landscape unit. One of the significant advantages of quantitative methods is the capability to represent continuous and discontinuous variation.

Segmentation of the continuum

Segmentation of the landscape continuum into horizons, profiles and spatial units presupposes structures that allow simplification and prediction. It assumes that there are better locations than others for drawing boundaries both laterally and vertically. These assumptions have been necessary to facilitate land resource survey using qualitative methods. The advent of digital technologies and quantitative methods has created opportunities for representing the landscape continuum in a manner that more realistically depicts natural variation. Some of these methods are now well established and can be used for survey. Other methods are still the subjects of research but if successful will be widely applied in the future.

Our view is that methods for depicting the landscape continuum should recognise that complex genesis and a low level of orderliness are common. Soil properties have varying degrees of correlation, and natural modalities may or may not occur. As a result, survey should aim to:

- measure and describe the continuum in terms of individual properties
- classify later if it is required for practical purposes.

The following sections consider various approaches to land resource survey in Australia. The main differences relate to the selection of entities (profiles versus horizons, sampling plans) and differences in spatial units. There is also a distinction made on the technology used for representing continuous variation, since digital methods have made this more feasible.

Methods of survey

The main approaches are introduced here for context. Details of each method and their strengths and weaknesses are considered in later chapters.

Qualitative methods

Integrated survey

Integrated survey refers to a general class of methods and includes land system surveys (Christian and Stewart 1968), soil–landscape surveys (e.g. Northcote 1984) and ecological surveys (Rowe and Sheard 1981). Most recent Australian surveys have used a variant of integrated survey.

Integrated surveys assume that many land characteristics are interdependent and tend to occur in correlated sets. Attributes observable on air photos, such as vegetation and landform, are used to predict the distribution of soil attributes that can be only observed at a few points in the field. They also assume that every land use is constrained by the combined and interacting

effects of several land attributes so the same land classification can be used to evaluate areas for a range of uses.

Soil survey (free survey)

The conventional form of soil survey is commonly referred to as *free survey* (Steuer 1961). It is suited to detailed-scale surveys and has been the method used for mapping in most developed countries. It was most commonly used in Australia prior to the 1980s, particularly for the development of irrigated agriculture. Some important contrasts with integrated survey are as follows:

- much effort is devoted to the development of a local soil classification prior to mapping
- the primary purpose of the mapping is to draw boundaries; descriptions (and modifications to the local classification) are made later
- the local classification is related by correlation to other local classifications to ensure some consistency between surveys.

Stratigraphic survey

The stratigraphic approach was developed by Butler (1958, 1967, 1982) and his colleagues (van Dijk 1958, Walker 1963, Churchward 1961, Beattie 1972). Similar ideas were developed in Africa and North America (Daniels et al. 1971). The approach places emphasis on the soil mantle rather than the profile. The stratigraphic relationships between the soil mantles provide evidence from which soil history can be deduced. In many Australian landscapes, this knowledge of landscape evolution and soil history provides a good basis for spatial prediction of soil attributes and ensures a better appreciation of landscape processes. A hybrid approach with elements of integrated survey and the stratigraphic approach is the *soil materials approach* described by Atkinson (1993). It has formed the basis for most of the land resource survey in New South Wales since the mid-1980s. See *Chapter 18* for details of methods for stratigraphic survey.

Qualitative grid survey

Grid survey is most commonly associated with quantitative methods (see *Quantitative methods*) but it has a long tradition in detailed qualitative surveys, particularly for irrigation development in flat landscapes. As its name implies, field sampling is based on a regular grid. In qualitative grid surveys, prediction at intervening sites usually involves manual interpolation to generate either land unit or isarithmic ('contour') maps of individual attributes. Qualitative grid survey is appropriate for intensive studies where air-photo interpretation is ineffective.

Quantitative methods

Geostatistical methods

Geostatistics provides methods for producing maps by contouring from dense grids of values estimated from more or less sparse sample data. The procedure for estimation is known as kriging. Research and development during the last 25 years has provided earth scientists with a sound technology that can be readily applied for estimating and mapping land resources. More recent versions of kriging can incorporate quantitative environmental data from digital elevation models and remote sensing. An introduction to the most useful forms of kriging for land resource survey is provided (see *Chapter 23*).

Correlation, regression and related methods for predicting soil attributes

A variety of statistical methods for correlation and regression can be used to implement another approach to quantitative survey that has become known as *environmental correlation*.

The term *SCORPAN* is also used (see McBratney et al. 2003 for the definitive review). The approach is an explicit analogue of conventional survey practice that aims to provide predictions for individual soil properties. Applications to date have relied heavily on correlations between soil properties and environmental variables derived from digital terrain analysis (see *Chapter 6*) and gamma radiometric remote sensing (see *Chapter 13*). If statistical sampling is used, statements of accuracy and precision are possible. The variation of individual soil properties can be portrayed as being either discrete, continuous or a combination of the two. Fine-grain predictions are provided that cannot be achieved with qualitative mapping. Environmental correlation is described in *Chapter 22*.

Hybrid methods

Quantitative methods have many variants. McBratney et al. (2003) provide a comprehensive review and highlight the complementary aspects of geostatistical and environmental correlation approaches.

In a similar way, environmental correlation can be used in a rule-based mode with the rules being developed through expert judgement, field data and models from other studies. Cook et al. (1996) formalised this approach using Bayesian methods to provide predictions of individual soil properties with estimates of uncertainty. McKenzie and Gallant (2006) provided another example where terrain variables and airborne gamma radiometric spectroscopy were calibrated with field stratigraphic observations to generate rules and predictions of individual soil attributes. In both cases, field knowledge was used to develop an explicit model for prediction. Both methods require a phase of statistically independent sampling before they can be considered to be technically defensible.

The transition from qualitative to quantitative methods

These *Guidelines* encourage a transition to quantitative methods wherever possible. The methods confer many advantages for prediction and interpretation of land resource information, but they also demand better organisation. New skills have to be acquired and considerable discipline exercised, particularly in relation to the management of large digital databases.

Quantitative methods are necessary so that static descriptions of land resources provided by qualitative surveys can be replaced by the prediction of individual attributes that control landscape dynamics (e.g. erosion, water movement, plant growth). This entails a close link to simulation modelling (see *Chapter 28*) and a careful appraisal of methods for measurement and spatial prediction.

The recognition that many integrated and free surveys do not provide a strong basis for predicting individual soil properties has been a motivation for the development of quantitative methods. Most survey programs have assumed that readily observed soil morphological properties used for field mapping are well correlated with more difficult to measure chemical and physical properties – this has been based more on hope than evidence. In many agencies, the assumption has not even been questioned because it is so entrenched in survey practice.

While there is a degree of correlation between soil properties, the substantial literature on spatial variation (e.g. Beckett and Webster 1971, Wilding and Drees 1983, Burrough 1993, McBratney and Pringle 1999) demonstrates that soil properties have no regular covariance. Furthermore, the proportion of variance in a particular attribute accounted for by a qualitative land resource map can be very low (e.g. < 50% and often < 30%). Of great importance is the inescapable reality that a large proportion of soil variation occurs over surprisingly short distances. Beckett and Webster (1971), in their landmark review, concluded: ‘up to half the variance within a field may already be present within any m² in it’.

Land resource surveys must strive to record and report the variation encountered in the field. Quantitative surveys use statistical methods to achieve this. Qualitative surveys that do not have a valid method for reporting the quality of mapping are no longer acceptable. A pragmatic approach incorporated into these *Guidelines* is for qualitative surveys to have a phase of statistically independent sampling. This provides a way of estimating the accuracy and precision of mapping at limited cost (see *Chapter 18*).

Selecting a survey method

Following is a brief overview of factors determining the most appropriate survey method for a given problem. Many of the themes are considered in detail in later chapters. Always remember that the critical issue is whether land resource information generated by a survey is able to change a decision-maker's choices. More specifically, determine whether a change in land management can come about through the survey information *reducing the uncertainty* about impacts of different strategies for land management (Pannell and Glenn 2000).

Nature of problem and resources available

Clearly specify the need for land resource information prior to commissioning the survey. The importance of well-defined objectives cannot be overemphasised because they should determine or influence every methodological decision. Likewise, the financial and technical resources and proficiency of the operatives constrain possible approaches (see *Part 3*).

Are quantitative predictions required?

There are applications where the need for quantitative prediction is well established because large investment decisions are involved (e.g. geotechnical studies, surveys for expensive remediation of contaminated sites) or legal implications are serious (e.g. environmental litigation). Although most land resource survey in Australia has been qualitative, the situation is changing. A major impetus is the use of land resource data as an input to simulation modelling. This modelling ranges from estimation of crop yield at the paddock scale through to continental assessments of net primary productivity and weather prediction (see *Chapter 29*). Knowledge of uncertainty is vital and for this reason all predictions arising from land resource survey should be accompanied by estimates of uncertainty (see *Chapter 24*).

Quantitative methods are also necessary for efficient data analysis when large quantities of field data are produced using sensors of various types (e.g. ground-based remote sensing).

Extent of region

Geostatistical methods are best suited to intensive studies of small regions where spatially dense sampling is feasible, with sites being located within the range of spatial dependence for each attribute. Larger regions will inevitably include landscapes with diverse histories and the contrasting patterns of soil variation will demand the determination of several sample variograms.

Methods of environmental correlation have been applied across large areas (e.g. 50 000 ha (McKenzie and Ryan 1999) through to the continental scale (Henderson et al. 2001)). It is simply the availability of cheap high-resolution environmental data that makes the approach suited to large areas. Integrated survey with independent validation is appropriate across large areas but the predictive capability of the method is often surprisingly poor (e.g. Beckett and Webster 1971, Beckett and Bie 1978).

Target variables and measurement

Well-designed surveys have a clear set of target variables that need to be measured and mapped (for detail see *Chapter 17*). Some variables are difficult to measure in a survey program because

of cost (e.g. soil hydraulic properties) or they vary with time. Several strategies may be needed: for example, a separate field measurement program to develop pedotransfer functions for soil properties that are expensive or difficult to measure (see *Chapter 22*), or establishing monitoring sites (see *Chapter 30*).

It may be necessary to have pilot surveys to determine whether a target variable can be measured and mapped with sufficient accuracy and precision for the desired purpose.

Landscape complexity

The survey effort needs to be tailored and an appropriate method selected to suit the complexity of the landscape. Some landscapes have complex histories and exhibit substantial short-range variation. They may be too complex to survey and only broad generalisations on soil variation will be possible. However, information on the magnitude of short-range variation is valuable in its own right for a range of land management decisions.

Is mapping necessary?

Land resource survey can provide valuable information for decision-makers without the production of a conventional map. An example is establishing baselines for soil and landscape attributes to support assessments of land condition. An accurate and precise estimate of the mean (e.g. pH, organic carbon) for defined region will be needed and this can be obtained through some form of randomised sampling (see *Chapter 20*).

Recommendations

There will always be a place for qualitative survey methods at a range of scales. However, this role is diminishing and new surveys should be quantitative wherever possible. Quantitative survey does not necessarily imply heavy investment in statistical and computing expertise – it can be achieved by adding a validation phase to the sampling program. This provides an objective basis for assessing the predictive power of a survey.

The capacity to reuse survey data is increasing dramatically through the use of digital information systems. It is therefore essential for surveys to be undertaken with a view to longer use and reuse of data (see *Chapter 25*).

Whatever method is selected, land resource survey methods should strive to be explicit, consistent and repeatable (Austin and McKenzie 1988). In an *explicit* method, each step is stated, assumptions are clear and subjectivity is declared. A *consistent* method yields results that can be related study to study. With a *repeatable* method, another operator can apply the procedure and obtain the same results.

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Scale

JC Gallant, NJ McKenzie, AB McBratney

Introduction

Many challenging aspects of land resource survey have resulted from unavoidable mismatches between the scales of measurement, estimation and prediction. Field measurements are often made at the scale of the soil profile or finer (length scale of centimetres). These measurements are sparsely distributed and are usually correlated with data that have much larger length scales. For example, slope and relief are often derived from either topographic maps or digital elevation models (length scales of tens to hundreds of metres) and information on geology is usually at a wider scale again (often thousands of metres). Finally, the results from a survey may be used at a range of scales, from the farmer's paddock through to national overviews.

This chapter provides a conceptual base for dealing with scale. The chapter starts with a set of definitions, a description of the scale hierarchy, and a consideration of patterns of soil variation. The practical issues involved in moving between scales, or mixing data from different scales, are then examined with an emphasis on the implications for land evaluation and simulation modelling. The chapter concludes with an outline of procedures for representing accuracy and precision.

Concepts

The scale hierarchy and geometric support

Soil and landscapes can be described as a nested hierarchy. Levels of organisation in this hierarchy can be ordered in both space and time. Lower levels are characterised by small areas and short times. Higher levels are characterised by large areas and long times. Spatial and temporal scales are not necessarily correlated (Blöschl and Sivapalan 1995).

Figure 3.1 represents the hierarchy of spatial scales for soil (see also *Hierarchy of land units*). The figure also represents different types of knowledge about soil and landscape processes. At any given level, horizontal axes represent the complexity of knowledge. The left (simple end) of one axis may represent the measurement of a single variable (e.g. pH) and the right (complex end) a variable calculated from a complex process model (e.g. for deep drainage). The other horizontal axis indicates whether the knowledge is mechanistic and based on an understanding of physical processes or, at the other extreme, purely empirical.

By necessity, field measurements in land resource survey are restricted to finite volumes sampled at sparsely distributed locations. The size, shape and orientation of the sampled

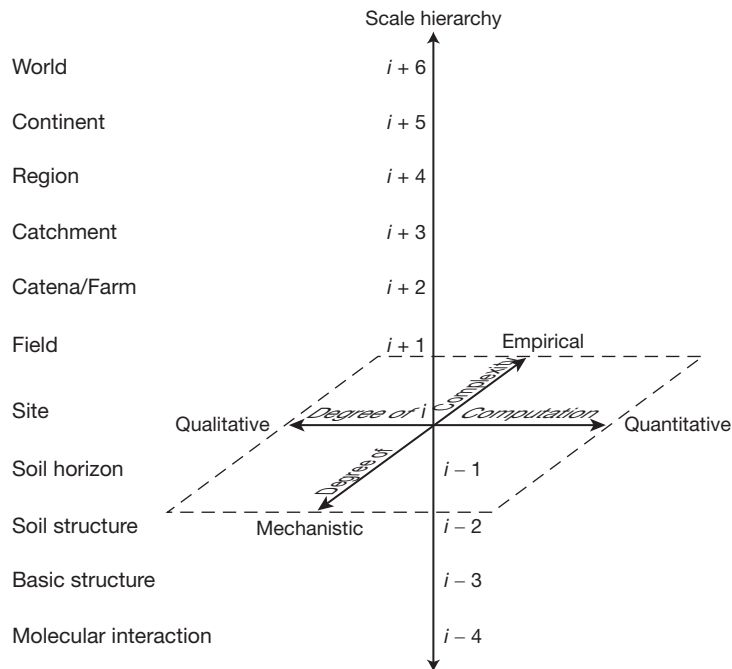


Figure 3.1 The hierarchy of spatial scales and types of knowledge relating to soils and landscapes (Hoosbeek and Bryant 1992; see also Bouma and Hoosbeek 1996 and Hoosbeek and Bouma 1998).

volume are known as the *geometric support* or, more simply, the *support*. The size of the support sets a minimum to the detectable spatial resolution. The supports for most field measurement are usually at levels i to $i-2$ (Figure 3.1).

Grain

Grain is the finest level of spatial or temporal resolution in an observation set or model. The concept of grain can be shown in a spatial context (Figure 3.2). The minimum grain will be set by the support (e.g. the pixel size of a remotely sensed image will depend on the resolution of the sensor). Alternatively, it will depend on the type of analysis used to generate values: for example, the grain of a digital elevation model depends on the support of the source data and the surface-fitting or smoothing algorithms. The models used to generate conventional soil and land resource maps are often complex, and the grain has been implied in a loose sense by the size of mapping unit.

Extent

Extent is the areal expanse or length of time over which observations with a particular grain are made, or a model with a particular grain is run (Figure 3.3). Changing the extent is easy, but changing the grain is not.

Scale

Manipulations of grain and extent enable us to translate information between scales. Coarse scales can be reached by increasing the grain and, usually, the extent of the observation set and

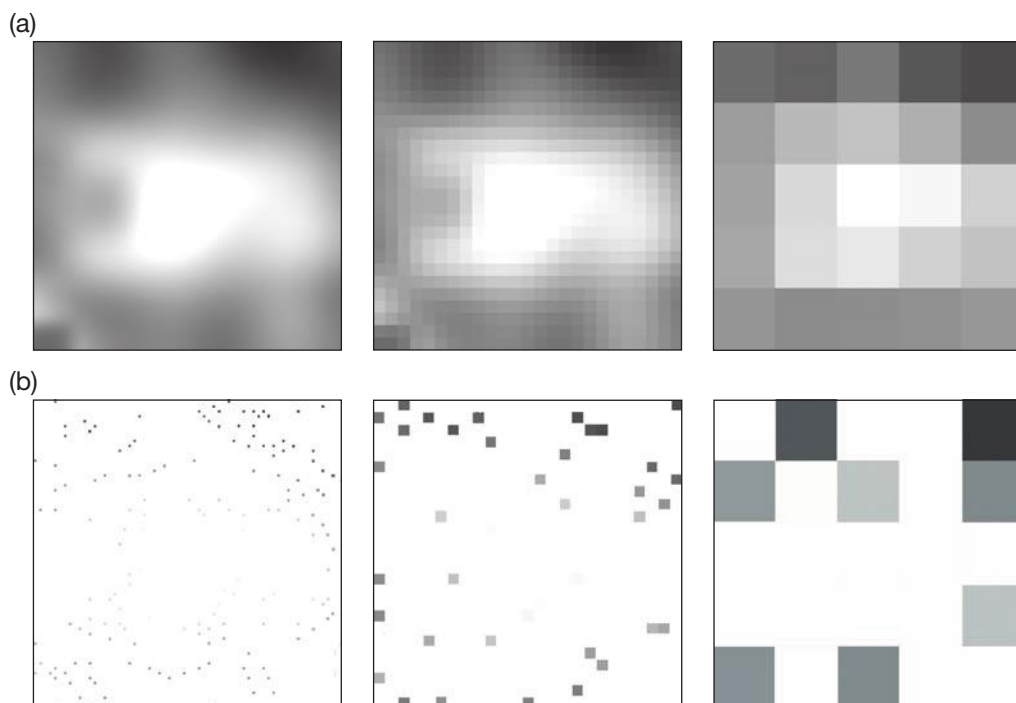


Figure 3.2 The concept of grain. (a) A soil attribute observed (from left to right) at increasing levels of graininess. (b) A soil attribute observed (from left to right) at increasing levels of graininess and with sparse sampling (blank represents no information). Providing values across the complete area will require some form of prediction as well as a change in scale (McBratney 1998).

this involves some form of averaging: for example, moving from subcatchments within a river system to basin-wide coverage. Going the other way (i.e. making the observation set more fine grained) is not straightforward.

Cartographic scale, the relative fraction and survey intensity

The terminology for ‘scale’ used within land resource survey has been at odds with that used in the biophysical sciences more generally. Land resource surveyors use the terms *small* and *large* in relation to the cartographic scale, or more specifically the relative fraction. The relative fraction is the ratio of distance on the map to that on the ground. The map distance is stated first as unity (e.g. 1:50 000).

If reference is being made to the cartographic scale, then state this explicitly. For example, a 1:10 000 map has a *large cartographic scale* while a 1:2 000 000 map has a *small cartographic scale*. Avoid the terms small, medium or large when referring to scale in a general sense and use descriptors such as detailed, intermediate or broad. For example, a 1:10 000 map is a *detailed-scale* representation and a 1:2 000 000 map is a *broad-scale* representation.

Cartographic scale has been used generally to describe the detail of mapping and convey the likely accuracy and precision. The concept of survey intensity was introduced to make a clearer distinction in a survey between cartography and field effort (see Valentine 1984). Survey intensity includes the number of observations per unit area, the precision of map unit descriptions, and the number of site descriptions for a locally defined soil profile class. Table 3.1 presents a classification according to cartographic scale and survey intensity. This table is useful but it is

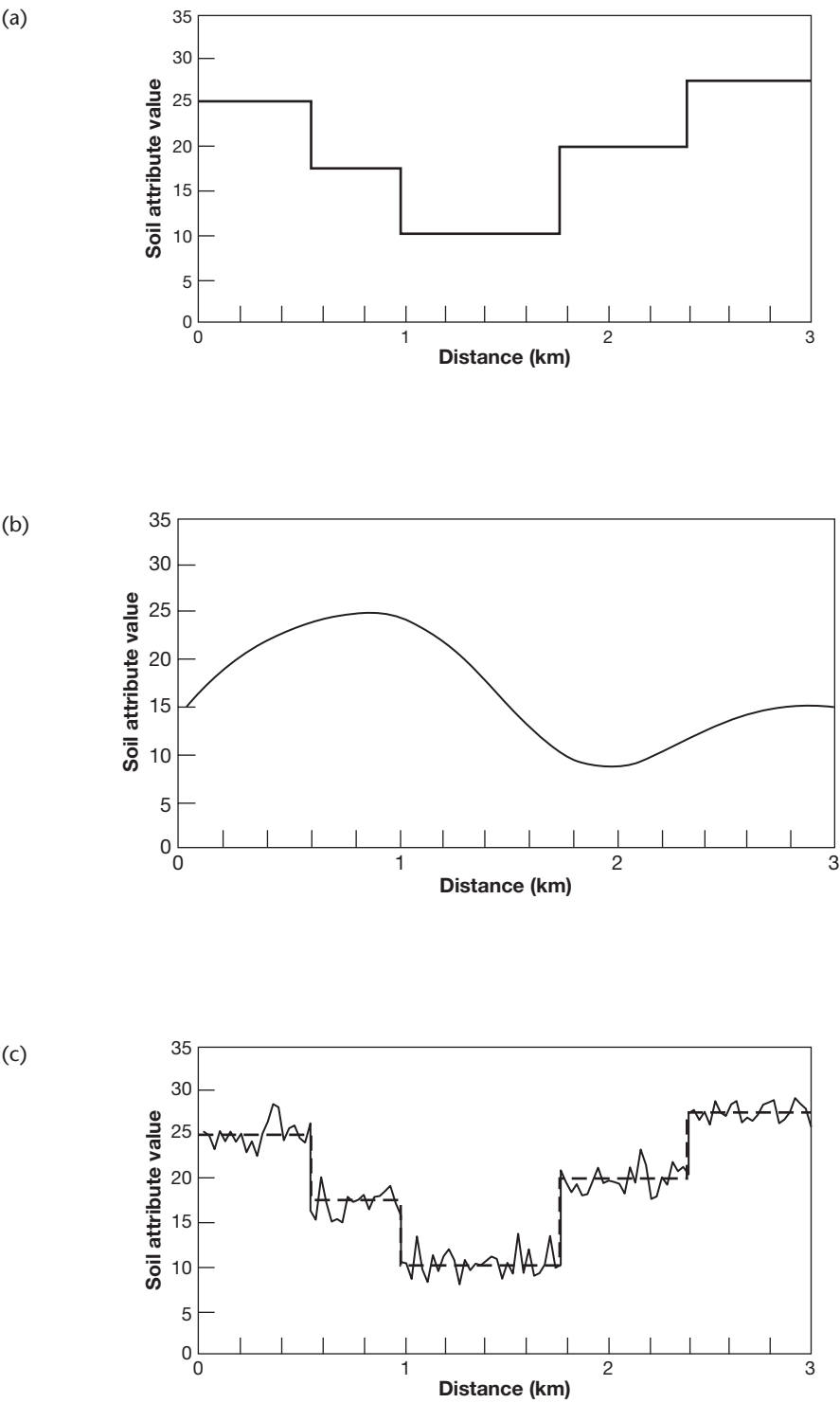
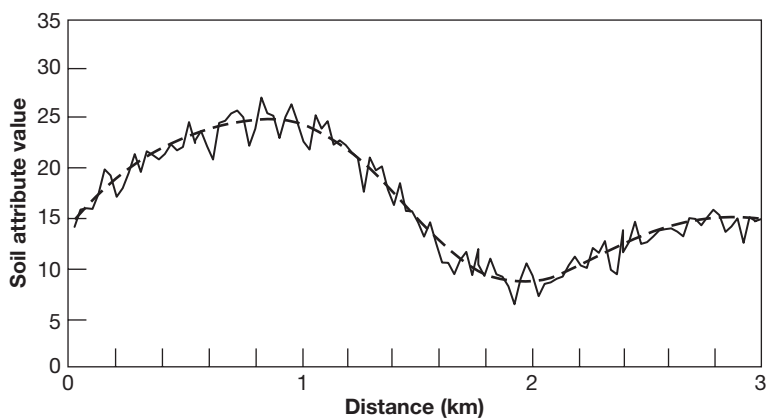
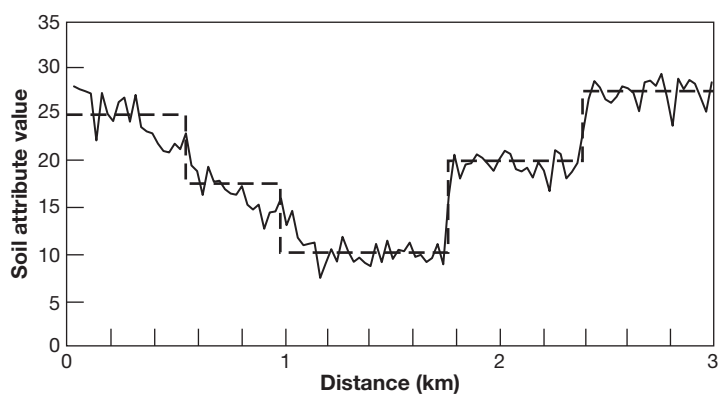


Figure 3.3 Potential models for soil variation along a transect: (a) discrete model, (b) continuous model, (c) discrete model with variation within tracts (after Burrough 1993).

(d)



(e)



(f)

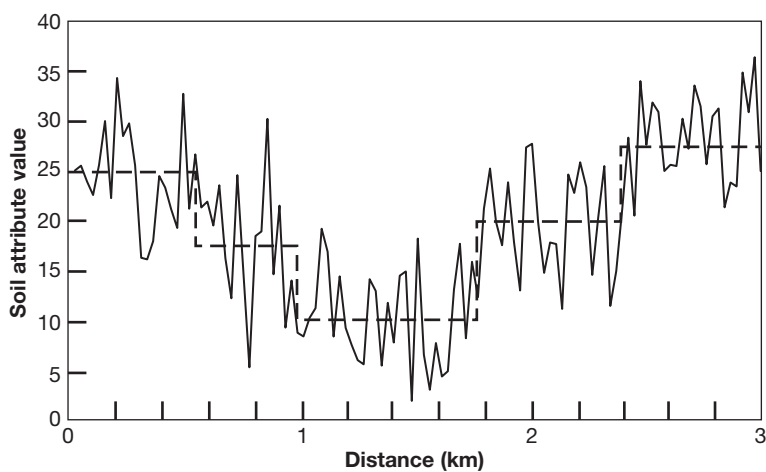


Figure 3.3 (Continued) (d) continuous model with variation, (e) mixed model with variation, (f) large short-range variation (after Burrough 1993).

Table 3.1 A classification of survey types according to cartographic scale and sampling intensity (after Rossiter 2000)

Intensity level	NRCS 'Order'	Inspection density	Publication scale	Minimum delineation size (0.4 cm ²)	Kind of map unit	Objectives
1. Very high (intensive)	1st	> 4 per ha; > 1 per 2500 m ²	1:2500	0.025 ha 2500 m ²	Simple, detailed	Site planning, detailed engineering, precision agriculture
2. High (intensive)	1st	1 per 0.8 ha to 4 ha i.e. 25 to 125 per km ²	1:10 000	0.4 ha 4000 m ²	Simple, less detailed	Intensive uses, small fields, urban land, sample areas, engineering works
3. Moderately High (Detailed)	2nd	1 per 5 ha to 25 ha i.e. 4 to 20 per km ²	1:25 000	2.5 ha 25 000 m ²	Mainly simple, some compound, moderately detailed	Moderately intensive uses at 'field' level, detailed project planning
4. Medium (semi-detailed)	3rd	1 to 5 per km ² i.e. 1 per 20 ha to 100 ha	1:50 000	10 ha	Mainly compound, some simple, moderately detailed	Moderately intensive uses at farm level, semi-detailed project planning, district level planning
5. Low (semi-detailed)	4th	1/4 to 1 per km ² i.e. 1 to 100 ha to 400 ha	1:100 000	40 ha	Almost always compound, or general simple	Extensive land uses, project feasibility, regional land inventory, district-level planning
7. Very low (reconnaissance)	5th	<1 per km ² i.e. <1 per 100 ha	1:250 000	250 ha 2.5 km ²	Compound or dominant simple	National land inventory, regional planning, very extensive land use
Exploratory		Opportunistic	1:1 000 000 1:5 000 000	40 km ² 1000 km ²	Categorically general	General information on new areas

not reliable for assessing the accuracy and precision of a survey. Other factors are important such as the complexity of soil variation in the region and power of the model used for spatial extension of point data.

Estimation

Measurements in surveys are commonly made on small supports (e.g. cores, specimens collected from soil pits) and the distances between sites are often large. They constitute a sample from the soil continuum. Estimation is the process of providing a numerical value for a population parameter (e.g. mean, median, standard deviation, variance) on the basis of the sample.

Prediction

Users of surveys often want to know the value for a particular soil variable at a specific location. In most cases, direct measurements will not be available for this location and the task facing the surveyor is to predict. Most methods for prediction can be seen as weighted averages of data that involve a systematic or deterministic component, and a random component. Webster and Oliver (2001) review these and some are introduced in later chapters.

Soil variation

Surveyors often assume a specific model of soil variation without providing supporting evidence. Figure 3.3 shows a range of possible models of soil variation (after Burrough 1993) – the extent of the abscissa could range from microscopic to continental.

Figure 3.3a depicts the conventional model of soil variation. It depicts abrupt changes at boundaries, but homogeneous soil between boundaries – this is known as the discrete, choropleth or polygon-map model. The continuous model shown in Figure 3.3b is often implied by integrated surveys. Soil is assumed to be correlated with landform and vegetation.

Figure 3.3c shows the choropleth model with little within-class variation and Figure 3.3d shows the continuous model with additional short-range variation. However, Figures 3.3e and 3.3f are more in accord with the empirical evidence for soil variation. In Figure 3.3e, there is a mixture of stationary (as per 3.3c) and continuous variation (as per Figure 3.3d). Figure 3.3f depicts a more complex, although widespread situation – short-range variation dominates and obscures all other signals. Figure 3.3 is restricted to a single variable. Soil is multivariate, and Figure 3.4 extends the ideas to two or more variables.

Entities for field-based measurement

Soil and landscape processes and their resulting properties are multiscaled (see *Chapter 5*). Ideally, soil properties should be observed at dimensions that match the scale of the relevant process. In remote sensing, measurements are made across the complete landscape and the key dimensions are defined by the grain and extent. However, field measurements of soil are restricted to small volumes sampled sparsely. The support and spacing of these observations determines whether coherent patterns can be detected. This is depicted in Figure 3.5 where several combinations of support and spacing are compared with the hypothetical variation of total phosphorous across a landscape. In Figure 3.5a the sample spacing is too large to capture the regular variation in the soil property and the variation of sample values appears random.

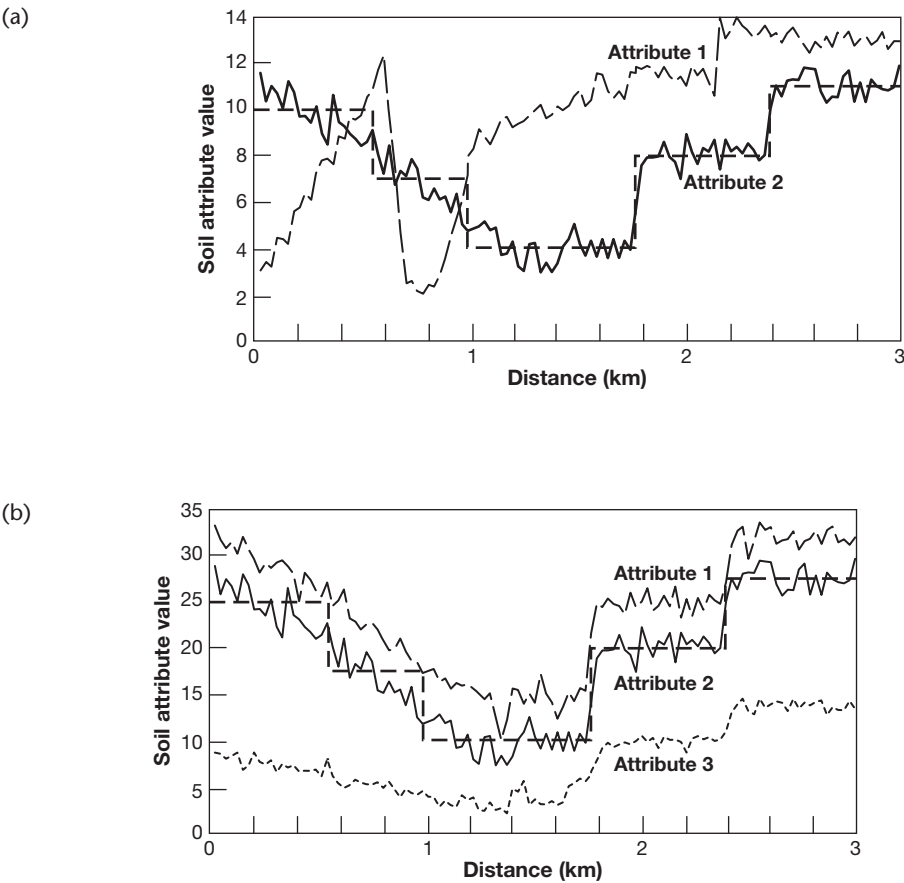


Figure 3.4 Potential models for multivariate variation based on Figure 3.3(e) with (a) weak and (b) strong covariance.

In Figure 3.5b the spacing is fine enough to see the variations but the extent is too small to capture the true nature of the variation. Finally, Figure 3.5c shows sampling that has an appropriate spacing and extent, but the large support reduces the apparent range of variation. A general relationship between observation and process scales is shown in Figure 3.6. While these concepts are helpful, apart from bulking (see *Chapter 20*), there is little flexibility with current technology to change support and, more significantly, soil properties inevitably arise from multiple processes at a wide range of scales.

The influence of unaided field observation

The supports used in survey have been set more by tradition and practicality than by careful analysis. The entities selected for measurement – such as soil horizons and profiles – relate to a scale of observation where the entity *appears* most cohesive, explicable and predictable. Allen and Hoekstra (1992) argue that the observer sets the scale of observation, so the entities tend to match human scales of unaided perception. For example, it is easy to describe the morphology

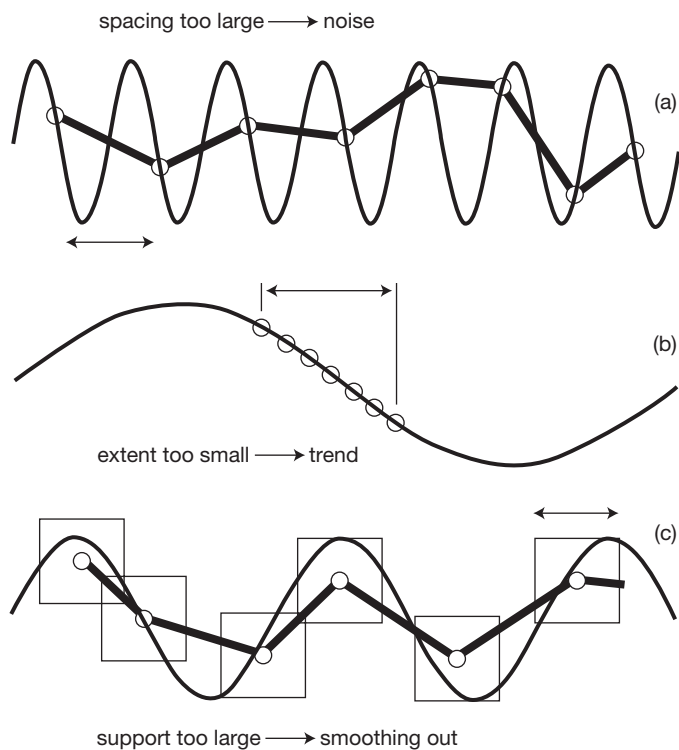


Figure 3.5 The observation scale is set by the geometric support and spacing of measurement. This may or may not be commensurate with the soil and landscape processes of interest (from Grayson and Blöschl 2000).

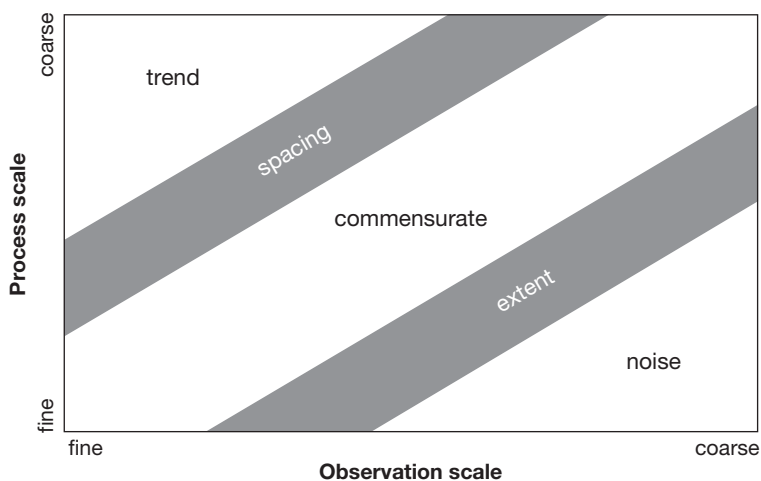


Figure 3.6 The general relationship between process and observation scales.

of a soil profile revealed in a pit, but extremely difficult to provide the same form of description for the much larger volumes of soil occupying a hillslope or catchment.

Logistic and technological constraints have forced surveyors to obtain data on supports much smaller than the areas over which managers want information (Williams et al. 2001). Practical methods for obtaining measurements at supports that relate more directly to plant growth and landscape processes are described in *Chapter 20*. Before these are considered, the literature relating to the specification of support in soil measurement is reviewed and, more specifically, the notion of the *representative elementary volume*.

Representative elementary volume

Support has been investigated mostly in relation to measurement in soil physics. For example, Anderson and Bouma (1973) measured the saturated hydraulic conductivity (K_s) of soil cores of varying height but with a diameter of 75 mm. They found K_s declined from 271 mm/h in cores with a height of 50 mm to 31 mm/h in cores with a height of 170 mm. The standard deviation also declined from 145 mm/h to 11 mm/h. A substantial portion of the short-range variation reported, particularly for hydraulic conductivity (Wilding and Drees 1983), probably results from the measurement methods being applied at inappropriate scales (Williams and Bonnell 1988).

Wherever structure has an important effect on the property of interest, the support should be varied as a function of structure. For example, macropores conduct water rapidly at potentials near zero, whereas they retain almost no water at negative potentials.

Where structure is evident, the volume should be large enough to contain a sufficiently large number of elementary units of structure (i.e. peds, pores) or repetitive units, typically at least 20 (e.g. Lauren et al. 1988). This volume is the *representative elementary volume* (REV) (Bear 1972, Wagenet 1985). Ideally the support should be chosen as the REV.

The definition of the elementary unit of structure is qualitative and can be difficult to apply in some soils; for example, elementary units may not be identifiable in the field in weakly aggregated and massive soils. The REV of some soils is too large for practicality (e.g. large columns and prisms in Sodosols and Vertosols). Williams and Bonnell (1988) measured large differences in hydraulic properties between tussock and bare areas in a north Queensland woodland. Similar differences are likely between the mounds and depressions of gilgai microtopography. An extreme case occurs in areas with outcropping rock. Buchter et al. (1994) provide a useful demonstration of the representative elementary volume concept in relation to coarse-fragment content. Williams et al. (2001) provide evidence from electromagnetic induction surveys to suggest that landscape hydrology is strongly influenced by variation with a scale requiring supports in the order of tens to hundreds of metres – this scale is overlooked in virtually all land resource survey because of current technologies used for measurement (see *Chapter 17*).

These are difficult problems to solve so bear in mind that soil variation is inherently multi-scaled, and conceptually there is no *a priori* reason to expect measurement variation to be small at a pre-specified scale. The convention of measuring soil on supports defined by cores or pits may be far from optimal. Although bulking is satisfactory in some instances, a general solution to the problem requires a fresh approach to soil measurement and this is a topic for future research.

Moving within the scale hierarchy

Upscaling and downscaling

Allen and Hoekstra (1992) recognised that, at various scales of perception, any phenomenon will appear simpler at some scale than it will at others (this notion is implicit in the representative

elementary volume). They suggest that robust prediction requires consideration of at least three levels of organisation:

- the level in question (e.g. $i + 2$, catena, in Figure 3.1)
- the level below – this provides insight into mechanisms (e.g. $i + 1$, soil individual)
- the level above – this provides context and significance (e.g. $i + 3$, catchment).

This line of reasoning suggests that predictive relationships developed at one level are unlikely to be useful for prediction at a level more than one level removed. Various aspects of land resource survey require movement within the scale hierarchy. Examples include:

- estimating average values for land units from a limited number of field observations
- estimating average values for land units (e.g. land systems) from averages for component tracts (e.g. land facets)
- relating field data to remotely sensed imagery where the support for the former is often several orders of magnitude smaller than for the latter
- relating nutrient data derived from very small supports to plant or crop performance across a field or larger tract
- estimating the value of a soil property at a given location from a map of land units (e.g. land facets)
- relating soil morphological, chemical and physical data to each other when they are all collected with different supports
- predicting landscape-scale processes (e.g. runoff, deep drainage, erosion, deposition) from site-scale measurements
- providing parameters for simulation models of processes at several scales.

All of these examples involve movement within the scale hierarchy, and the steps involve some form of downscaling or upscaling (Figure 3.7). Scaling literally means to reduce or increase in size. Upscaling is a popular term that refers to transferring information from a given scale to a coarser scale – it involves moving up the hierarchy in Figure 3.1, either through enlarging extent, or coarsening grain, or both. Downscaling is the opposite process (Blöschl and Sivapalan 1995).

Some forms of upscaling are trivial. For example, it is straightforward to compute the mean organic carbon content for a field when there are many determinations made on soil specimens collected in a small corer. It is less clear how to calculate a regional mean for organic carbon when average values are available for soil profile classes across a district, although some form of area-weighted average would be logical. Soil properties that are non-linear cannot be simply averaged in the same way as organic carbon (Webster and Burgess 1984). Calculating area-weighted means (or more appropriately, area-weighted geometric means) for a property such as hydraulic conductivity will be less than satisfactory in most instances. It will often be the extremes of the distribution that determine behaviour at the coarser scale: for example, small areas of impermeable soils may have a disproportionate effect on runoff, while some permeable zones may control groundwater processes. The weakest steps in current practice relate to disaggregation and distributing.

In most cases, options for upscaling will be clearest when the distribution function for individual soil and landscape properties is known. The challenge for land resource survey is to express the results of spatial predictions in the form of distribution functions. At its simplest, this involves an estimate of the form of distribution function (e.g. normal, log-normal, triangular, rectangular) along with an estimate of the mean and variance (see *Representing uncertainty*). Conceivably, distribution functions could be used for downscaling, but we cannot provide guidelines.

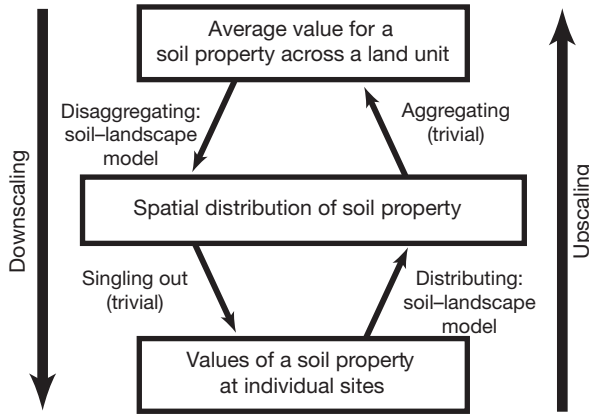


Figure 3.7 Movement within the scale hierarchy involves upscaling and downscaling – some forms of which are trivial while others are technically demanding.

Hierarchy of land units

Requiring observation scales to match process scales has many implications. First is the recognition of emergent properties. As one moves through the scale hierarchy, some variables have a scale over which they are most useful – they *emerge* at particular scales. For example, aspect is an attribute of landform that is particularly useful at the scale of the hillslope – it becomes less useful when dealing with broader tracts of land. Likewise, measurements of groundwater levels are often more informative than detailed determinations of soil hydraulic properties when information is needed on directions of flow across areas of several square kilometres – groundwater level integrates the effects of many subsidiary variables. The concept of emergent properties is implicit in the hierarchical schemes used for classifying spatial units in Australia (e.g. Table 3.2).

The terminology used to define spatial units in Australia has been confused despite the pre-eminence of Australian workers in land resource survey and the existence of a well-defined literature (e.g. Stewart 1968, Austin and Basinski 1978, Dent and Young 1981, Gunn et al. 1988). People have applied terms such as land unit, land system and unique mapping area in various ways. Speight (1988) brought order to the situation, and we use his recommendations on terminology because they are consistent with most aspects of current practice. They are also broadly consistent with international terminology (e.g. Dent and Young 1981).

Speight (1988) used *land unit* as a generic term and in a sense different from that of Christian and Stewart (1968). *Land unit* does not imply a particular scale, and it can be used to refer to conceptual units, mapping units (e.g. a *tract* of land or an individual polygon) and taxonomic units (e.g. a *type* of land such as the Oxford Land System).

Speight (1988) also defined a *land unit individual* – this is a particular area of land having the same size as the land unit *characteristic dimension*. Users of the ‘Field handbook’ (McDonald et al. 1990) will be familiar with this notion through the site concept. For example, landform element attributes are observed over a circle (the site) of about 40 m diameter – the site in this instance defines the land unit individual and its characteristic dimension. In contrast, landform pattern attributes are observed over a circle of about 600 m diameter.

Speight’s (1988) and Speight and McDonald’s (1990) observations on the characteristic dimensions of landform elements and patterns were intended as guides rather than fixed

values. The concept is far more valuable than this, and it is used here in conjunction with sets of defining attributes to construct the *hierarchy of land units*.

Each level in the hierarchy of land units (Table 3.2) has a specified characteristic dimension along with a set of defining attributes measured at the accompanying scale. The characteristic dimension can be viewed as the grain or window size over which the defining attributes can be sensibly measured – different landscapes will have contrasting characteristic dimensions. For example, hillslope lengths may be very short (only a few metres in a strongly gullied landscape) or long (> 1 km in strongly weathered landscapes of low relief), so land facets of very different size result. In some landscapes, nested patterns of landform may be evident, and sublevels

Table 3.2: The spatial hierarchy of land units (after Speight 1988 and McKenzie et al. 2005)

Level	Order of land unit	Speight	Characteristic dimension	Appropriate map scale	Defining attributes
1.0	Division	300 km	30 km	1:10 million	Broad physiography (slope and relief) and geology
2.0	Province	100 km	10 km	1: 2.5 million	Physiography, water balance, dominant soil order and substrate
3.0	Zone	30 km	3 km	1:1 million	Physiography, regolith materials, age of land surface, water balance, dominant soil suborder
Mapping hiatus					
Below is generally aggregated from surveys, above is based on subdivisions of the continent					
4.0	District	5 km	1 km	1:250 000	Groupings of geomorphically related systems
5.0	System	600 m	300 m	1:100 000	Local climate, relief, modal slope, single lithology or single complex of lithologies, similar drainage net throughout, related soil profile classes (soil–landscape ^A)
5.1			100 m	1:25 000	As for Level 5.0
6.0	Facet	40 m	30 m	1:10 000	Slope, aspect, soil profile class
6.1			10 m	1:2 500	As for Level 6.0
6.2			3 m	1:1 000	As for Level 6.0
7.0	Site			Rarely mapped in conventional survey	Soil properties, surface condition, microrelief

Note that sublevels can be characterised (e.g. a System with a characteristic dimension significantly less than 100 m would be designated by Level 5.1).

within the hierarchy can be sensibly delineated by the same set of defining attributes at more than one characteristic dimension.

The estimates of characteristic dimension in Table 3.2 have been changed from Speight's (1988) original proposition to emphasise the role of the characteristic dimension as a variable that defines both the appropriate scale of measurement and the nature of the landscape (i.e. the process scale). The suggested values also better match the styles of survey undertaken across large areas during the last 15 years.

Most land resource survey in Australia is concerned with the mapping and description of land units at the *land facet* and *land system* level. Speight (1988) defined these as follows.

- *Land facet*: This is a land unit with attributes that include slope, aspect, toposequence position, microclimate, moisture regime, soil profile class, land surface features, vegetation formation and vegetation community. Speight (1988) considers its characteristic dimension to be about 40 m but it can vary from 100 m to just a few metres. Note that the terms *land component* and *land element* have often been equated with this definition of land facet.
- *Land system*: This is a land unit with attributes that include relief, modal slope, stream pattern, toposequences, local climate, lithology, soil association, vegetation type or sequence, and proportional occurrence and arrangement of land facets. Speight (1988) considered its characteristic dimension to be about 600 m, and he recommended this diameter for a land system site.

These are definitions of conceptual land units. Explicit reference can be made to land-unit individuals, types or tracts (e.g. land-facet individual, land-facet tract, land-facet type) but the context will usually convey the appropriate meaning. Particular mention should also be made of *unique mapping areas* – these are usually instances of land-system tracts that are later grouped into land-system types.

If land facets and land systems are defined in terms of landform attributes alone, they are identical with the landform elements and landform patterns defined by McDonald et al. (1990).

Mapping land districts is usually achieved by grouping land systems. Mapping land units at higher levels can be achieved by grouping land districts, but, in reality, most mapping at the division, province and zone level is undertaken by a divisive rather than an agglomerative approach. Furthermore, different criteria for mapping emerge at these broader levels, and many of the criteria used at lower levels lose significance (and *vice versa*). Refer to the Australian Soil Resource Information System (2006) for an implementation of the hierarchy of land units.

Representing uncertainty

The need to sample, measure, estimate and predict at different scales results in varying degrees of uncertainty. Make every effort to estimate this uncertainty because it is fundamental to the utility of land resource survey (see *Chapters 1, 24 and 28*, Heuvelink 1998, Moss and Schneider 2000). Remember that surveys become useful when the information reduces the risk for decision-makers – they need to know its uncertainty. In many instances, the information on uncertainty is as important as the mapping.

The following guidelines for evaluating and expressing uncertainty are from Taylor and Kuyatt (1994) and McKenzie et al. (2005).

Type A evaluations of standard uncertainty are based on any valid statistical method for treating data. See *Chapters 20, 22 and 23* for some of the basic equations necessary for the task. An example would be estimation of the mean and variance for soil properties measured after stratified random sampling of a land unit. Type A evaluations are not common in Australian surveys.

Type B evaluations of standard uncertainty are based on scientific judgement using all the relevant information available, which may include:

- previous measurements on related soils
- experience with, or general knowledge of, the behaviour and properties of the relevant soils and measurement methods (e.g. accuracy of laboratory determinations and field description methods, reliability of pedotransfer functions)
- uncertainties published in reviews of spatial variation (e.g. Beckett and Webster 1971, Wilding and Drees 1983, McBratney and Pringle 1999).

Most estimates of uncertainty in conventional land resource survey have to rely on Type B evaluations. The form of the estimate depends on the measurement scale and assumed probability distribution for each attribute. Use the following as a starting point.

- Continuous variables with an assumed normal probability distribution have their uncertainty represented by an estimated standard deviation. This is denoted by u_i and u_j for Type A and B evaluations respectively. In most cases, uncertainty will arise from several sources and the combined standard uncertainty (u_c) is reported. There are many issues to resolve in calculating (u_c) and it will often be appropriate simply to assume the component variances are additive (i.e. $u_c = \sqrt{u_1^2 + u_2^2 + u_3^2 \dots}$) where u_1 , u_2 and u_3 are sources of uncertainty attributable to different sources – for example, measurement, a pedotransfer function or spatial variability).
- Continuous variables that are not normally distributed (e.g. hydraulic conductivity, electrical conductivity) are transformed to an approximately normal distribution and uncertainties then estimated. Hydraulic conductivity and electrical conductivity are assumed to be distributed log-normally, unless there is evidence to the contrary.
- Variables with fixed ranges (e.g. percentage coarse fragments) or coarse-stepped scales can be modelled with rectangular probability distributions (bounded by 0 and 100%) unless there is evidence to the contrary.
- Uncertainties for nominal variables can be represented by the probability that a class is correct (e.g. the probability that a landform element type is a beach ridge is 0.8). Combined uncertainties are calculated by multiplying component probabilities.

The uncertainty associated with predictions of soil properties from land resource survey can be viewed as having at least two general components.

1. Associated with the measurement error – it will be significantly reduced if replicated sampling or bulking has been undertaken. If the attribute (e.g. water retention at –10 kPa) is being estimated using a pedotransfer function, then the uncertainty includes both the measurement error of the explanatory variables (e.g. texture, structure, bulk density) and the strength of the pedotransfer function used for estimation.
2. Spatial variability within the land unit.

In most parts of Australia, there is little information on both of these sources of uncertainty and it will require good judgement to provide estimates. However, the practice of providing estimates of mean values without information on variation might be misleading.

In the absence of better information, use default values of uncertainty drawn from the published literature on spatial variation. Ensure these are conservative (i.e. most likely on the high side) and encourage more attention to the estimation of uncertainty.

Default estimates of uncertainty for soil and land attributes in the Australian Soil and Land Resource Information System are presented by McKenzie et al. (2005). Formal procedures for tracing uncertainty in spatial prediction and simulation modelling are also considered (see *Chapter 24*).

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Part 2

Landscape context and remote sensing

Many landscape attributes are correlated with soil properties and some of the former are useful for mapping. The following chapters vary in scope. Those on geology, soil and landscape processes, terrain analysis, hydrology, land use and remote sensing serve as guides to large subject areas. The chapter on vegetation provides guidelines for the capture, interpretation and management of vegetation data. Many of the methodological procedures and challenges in soil survey have close parallels in vegetation survey.

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Geology, geomorphology and regolith

G Taylor, CF Pain, PJ Ryan

Introduction

Rocks are the starting material for nearly all soil. They weather to produce regolith, which is eroded, redeposited and cemented. The regolith above the rock hosts, at its surface, the pedologically organised materials called soil. Landscape embodies all the various topographic features over a particular region. At the broadest scale, it consists of mountains, plains and valleys, with some abrupt features such as escarpments. Most often landscape is what we see from a particular viewing point: a plain with isolated hills, a set of ridges and valleys, an alluvial plain with abandoned meanders.

These concepts transcend scale to some extent – the definition depends to a large degree on the scale of observation. At a coarse scale (kilometres), a granitic terrain may consist of rounded hills with sandy streams occupying the valleys. At the scale of one hillside (100 m–1000 m), the landscape may consist of rounded boulders (tors) sitting on the upper hillside, with a sandy colluvial sheetwash forming a relatively smooth inclined surface between the tors, aggrading into a thick mantle of sandy colluvium and alluvium in the lower slopes. And there are patterns at even finer scales.

The original minerals and rocks formed under various conditions that can be characterised by certain combinations of temperature, pressure and chemical species. When they find themselves at or near the surface, they come under different regimes of temperature, pressure and chemical environment and they begin to weather. Thus, poorly cemented mudstones that have been buried in a sequence of coal measures can, upon exposure via open-cut mining, rapidly disintegrate because of the change in pressure. Within an igneous rock such as granite, which is formed at high temperature and pressures, individual minerals can, when exposed to surface environments, differ in their stability. Quartz, for instance, is fairly stable and will long remain in the weathered granite regolith; biotite, in contrast, will weather rapidly to clay. The weathering environment has changed over geological time. The Paleogene and Neogene were wetter, and sometimes hotter, in Australia than now. Regolith can therefore display weathering features that have been inherited from prior climatic environments (see *Chapter 5*).

Most landscapes have a general but distinct relation to geology. For example, rocks that weather slowly (quartzite, slate) form higher landscape elements than those that weather more quickly (basalt, shale). Similarly, regolith character may influence or modify landscape in a manner different from the underlying bedrock. For example:

- aeolian dust can cover the land, obscuring the underlying weathering bedrock with material of different mineralogy and particle size
- weathering can produce duricrusts within the regolith that can be resistant to erosion and can thus control landscape morphology.

Landscape can also influence surface and near-surface processes and therefore regolith development. For example, the lower parts of many hillslopes are covered by colluvial deposits that have resulted from either mass movement or sheetwash or both.

Time is important in the formation of regolith and landscapes. Australia has significant areas of Precambrian bedrock, and there are also large outcrops of younger rocks that have been exposed to weathering for long periods without significant erosional disturbance. This has produced thick, strongly weathered regolith. Other regions of Australia have complex geomorphology, with a history of stability punctuated by catastrophic changes.

In many places rocks that would not normally be expected to exhibit karstic landform features (typically found in limestone countries) do so. For example, many Cretaceous sandstones across Northern Australia are karstified and east of Darwin, near the Mary River, a Proterozoic syenite has a karstic surface. Although these rocks are usually assumed to be fairly insoluble, exposure to rain has enabled karst to form on these rocks. Similarly, ephemeral tectonic activity has, over long periods, created exceptional landscape and regolith features. The formation of Lake George (Abel 1991) is a good example where drainage was progressively disrupted over the last 5 million years and an internally draining lake basin formed. Taylor and Walker (1986) provide a similar example: Lake Bunyan, near Cooma, existed 10–20 million years ago and the regolith formed in the lake sediments explains many of the anomalous soil distribution patterns noted earlier by Costin (1954). Landscape and regolith evolution in these regions is sensitive to the timing, over long periods, of repeated faulting.

Although time is an important factor in the development of landscapes and regolith, dating the evolution of either is not easy. Ollier and Pain (1996), Pillans (1998) and Taylor and Eggleton (2001) provide summaries of suitable absolute and relative dating methods.

There is, thus, a complex interrelationship between rocks, regolith and landscape. This must be comprehended to ensure surveys are undertaken with the necessary understanding of the processes that form regolith, soils and landscapes (see *Chapter 5*).

Some definitions for regolith

Eggleton (2001) gives a comprehensive glossary of regolith and related terminology. Here the important definitions for present purposes are listed.

Regolith (Jackson 1997) is ‘the layer or mantle of fragmental and unconsolidated material, whether residual or transported and highly varied in character, that nearly everywhere forms the surface of the land and overlies the bedrock’. Another simpler definition for regolith is everything that lies between fresh rock and fresh air. The only addition to this definition the authors make for Australia is that it may include more or less strongly cemented materials known as duricrusts. The regolith may consist of weathered bedrock that remains *in situ*, moved weathered bedrock (collapsed saprolite or mobile zone), sedimentary materials derived some distance from their present position, or a combination of the three. Commonly used vertical subdivisions of *in situ* regolith are shown in Figure 4.1.

Duricrust is a part of the regolith cemented at or near the surface. Common cementing media include iron oxyhydroxides, aluminium oxyhydroxides, silica, a variety of carbonate minerals (most commonly calcite), and manganese oxyhydroxides. Duricrusts cemented by these various cements are called ferricrete, bauxite (alcrete), silcrete, calcrete and mangano-crete, respectively.

Saprolite is weathered bedrock in which the fabric of the parent rock, originally expressed by the arrangement of the primary mineral constituents of the rock, is retained (Eggleton 2001).

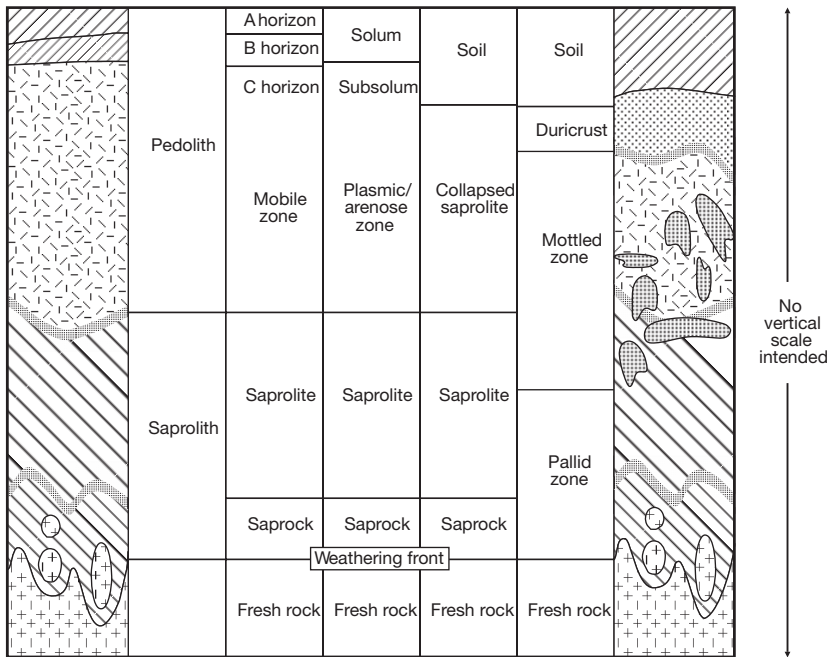


Figure 4.1 Commonly used vertical subdivisions of in situ regolith (from Taylor and Eggleton 2001). Note that the term *regolith* also includes transported materials, not shown here.

Soil is the unconsolidated mineral matter at or near the Earth's surface that has been subjected to, and influenced by, environmental factors such as weather, macro-organisms and micro-organisms, and topography; all act to form a soil that differs – in many physical, chemical, biological and morphological properties and characteristics – from the material from which it is derived (Eggleton 2001). It generally forms the uppermost part of the regolith and has as its parent material the regolith.

Weathering refers to any process at ambient temperature and atmospheric pressure that, through the influence of gravity, the atmosphere, hydrosphere and biosphere, modifies rock either physically or chemically.

Lithostratigraphy is the organisation of a sequence of rock strata on the basis of their lithological character (the chemical composition of a rock type). Such lithostratigraphies do not necessarily correlate with stratigraphies defined by time. In many cases there may be a correlation between time-stratigraphy and litho-stratigraphy, particularly where the time divisions used are coarse.

Earth data resources

Land resource survey makes use of geological information, including maps and reports of geology and regolith, results of landscape and geophysical surveys, borehole data, exploration geochemical surveys and groundwater information. Surveyors can expect to seek such information from several sources and assemble it. Sources include Geoscience Australia, state geological surveys, land and water resource agencies, universities, mineral exploration companies (often reports lodged with geological surveys) and similar organisations around the country. A good starting point in Australia is the Geoscience Portal provided by Geoscience Australia (Australian Government Geoscience Portal 2006).

Geological data

Interpretation

Geological mapping, at least at a first pass, is available for the whole of Australia and, for certain places, successive and more detailed surveys are available. It is necessary to know how to use geological data. Most maps available provide data on 'mappable geological units' (i.e. many of the polygons on the map are heterogeneous) based on lithological or systematically varying lithological data. Mapped units often comprise 'Formations' and 'Groups' – sedimentary or volcanic sequences that may be made up of a variety of lithological types. Intrusive igneous rocks are generally mapped according to lithology, as are lavas. Lithologies are also often divided according to age, which from the point of view of soil or land survey is somewhat unnecessary as it is the lithology that influences soil properties and (together with geological structure) landform. Few geological maps portray simple lithologies because they are usually drawn at such a small cartographic scales that differentiation is impossible. Thus, most geological maps contain descriptions of polygons that resemble the following examples. From the Canberra 1:100 000 Geological Sheet 8727 (Abel 1991):

- *Mount Painter volcanics* (Smp) – dacitic ignimbrites with lithic xenoliths and dacitic autoliths, minor tuff and ashstones.
- *Adaminaby beds* (Θa) – interbedded sandstone, siltstone, shale and hornfels.
- *Quaternary alluvium* (Qa) – gravel, sand, silty clay and black organic clay alluvium.

From the Yarraman Special Geology Sheet, 1:250 000 (Cranfield et al. 2001):

- *Boondooma igneous complex* (PTgb) (Tgbo) – granodiorite, adamellite, granite, tonalite, diorite, gabbro and cream to pale grey fine- to medium-grained equigranular coarsely porphyritic biotite–hornblende granite;
- *Gayndah formation* (Ttg) – polymictic pebble to cobble conglomerate; lithic labile, sublabile and quartzose sandstone, siltstone, shale.

These units contain ranges of lithologies that behave very differently both as soil parent materials and in their influence on landscape evolution. Gray and Murphy (1999) predict that soils developed from rocks such as gabbro, granodiorite, lithic sandstones and quartz sandstone would be different under similar climatic and drainage conditions. For youthful sites with imperfect drainage and a semi-arid environment, they predict the most common soils formed from each lithology to be, in order, Vertosols, Sodosols and Yellow Chromosols.

Another important feature of most standard geological maps is that they are primarily concerned with bedrock geology and not regolith. Note the definition of 'Quaternary alluvium' above. Thus, the geological map unit may provide limited guidance on the current mineralogy or geomorphology of the regolith. Moreover, most geological maps take no account of alteration or weathering, to the point that often only a small proportion of the surface rocks in a mapped polygon matches the description in the legend. This is because most are compiled for mineral explorers, who need very different information from land managers and surveyors.

Despite this, geological maps are usually valuable. To gain advantage, surveyors need to learn how to read them and understand the basis of mapping and the variation within and between polygons.

Most sedimentary and volcanic sequences in the geological record are mapped in the field on the basis of the *Formation*. This is defined as 'a mappable unit of rocks'. The first obvious conclusion from this definition is that what is mapped depends on the cartographic scale at which the mapping is done. Most geological maps in Australia are compiled at 1:25 000 or 1:100 000 scales and published at 1:100 000 or 1:250 000 scales respectively. Second, and less

obviously, a formation may consist of one lithology (e.g. Hawkesbury Sandstone or Acton Shale). Generally, lithology is reasonably uniform when a lithological name is used to define a formation. In the case of Hawkesbury Sandstone, it is predominantly quartz sandstone, but the unit also contains significant lenses of shale that provide regolith and soil parent material locally that contrasts with that from quartz sandstone. Where the Hawkesbury Sandstone outcrops, most geological maps do not show the shales separately. In other cases, where the word 'Formation' is used to describe a lithostratigraphy, it is likely that the mapping unit contains diverse lithologies. Where these lithologies are thinly interbedded (e.g. quartz sandstones and shales) the consequences for soil parent material are probably not significant. An example is the Pitman Formation around Canberra where thinly interbedded quartz sandstone and shales (on a scale of several metres) form a clayey-sand parent material. However, because the shales weather much more than the quartz sandstones, they develop a thick regolith (up to 10 m), in contrast to the very thin (< 1 m) regolith or rock outcrop on the sandstones, on which shallow Leptic Rudosols and Tenosols occur.

For other formations the use of the word 'Formation' implies lithological variation within the map unit. An example from the Late Devonian of the South Coast of New South Wales is the Worange Point Formation. This unit is clearly mappable in the field, but consists of red shales and reddish-grey sandstones. Furthermore, it varies spatially in its sand to shale ratio. It is defined by its lithostratigraphic relationships as well as its lithological variety.

The other most important information to be gleaned from geological maps is about geological structures. Many geological structures at various scales have major controls on landscape evolution and, as a consequence, on the distribution of landscape features and regolith materials. The position and nature of large features such as faults can be gleaned from geological maps. The comparison of their position with major landscape elements provides explanations for the morphogenesis. Features such as jointing can determine drainage patterns. Folding of rock bodies also gives clues to the controls on the distribution of landscape elements as well as on soil patterns. Lithology and folding can produce repetitive patterns across landscape and geological elements.

Sources of geological data

Geoscience Australia and the state and territory geological surveys produce geological maps. They publish mainly at 1:250 000 and 1:100 000 scales, and occasionally, at 1:25 000. The availability of maps can be determined from the Geoscience Portal and its many links. Table 4.1 lists information that can be obtained from standard geological maps. In addition, maps, generally at detailed scales, are available from mineral exploration leases via completion reports lodged with state and territory geological surveys.

Landform data

Landform, represented by topographic maps or digital elevation models (see *Chapter 6*), reveals much about geology, regolith and landscape. Assessing landform depends on scale. At coarse scales, topographic maps can provide information on aspects such as geological controls of landform patterns. Figure 4.2 displays extracts from 1:250 000 topographic and geology sheets for Dixon Range. The close correlation between landform and geology is clear at this scale, and division into landform patterns is possible (e.g. hills, alluvial plains, erosional plains, alluvial and colluvial fans). This gives an insight into the dominant processes operating through the evolution of the landscape. To gain insight into more detailed processes, finer representations of the landscape are needed. For example, minor landslips often cause hill slopes to become hummocky with a local relief of a few metres. This type of activity cannot be assessed in

Table 4.1 Key information from standard geological maps

Primary data	Secondary data	Data type
Lithology		Polygons, line types, and table
Age and stratigraphic relationships		Table
Source of information and relative accuracy		Reference text
	Reliability diagram	Small polygon map
	Boundary accuracy	Line type
Structure		
	Major units	Small polygon map
	Faults and shears zones	Line type
	Fold axes: anticline, syncline etc.	Line type and symbols
	Lineations	Line type
	Unconformities, disconformity	Line type
	Dip, strike, foliation, cleavage	Point symbol
Location of mines, quarries etc.		Point symbol
Cross-sections		Line type and separate polygon diagram

landscape images of coarse scale – in most cases it is evident at cartographic scales only more detailed than 1:10 000 or from field observations.

Regolith data

Regolith is the uppermost part of the solid Earth above fresh rock – including all weathered rock, unconsolidated and consolidated sediments and, in some cases, volcanic debris. Data collected on regolith are highly varied. In regions where there has been detailed field work to provide information in the vertical dimension, fine-scale data on the three-dimensional distribution of regolith materials are available (e.g. Lawrie et al. 2000). Most data are in the form of regolith landform maps (e.g. Pain et al. 1994, Chan and Fleming 1995, Chan et al. 1995). These are produced in the same way as soil–landscape maps are made: regolith materials on similar landforms are assumed to be similar. This model derives from the idea that landforms are controlled by geology and surface processes and therefore it is most likely that regolith materials will vary similarly. Accordingly, one can delineate landscape units from aerial photographs or digital elevation models and, after field checking, ascribe to each landscape polygon a characteristic regolith material. The vertical dimension is generally depicted by map unit descriptions or by sketches of typical regolith catenas (sequence of soils down a hillslope). The data conveyed relates to landscape and regolith and the latter includes the nature of the regolith material.

Most commonly, regolith data relate to surface expression and the vertical dimension is inferred from data from pits, cuttings and other vertical exposures of the regolith; alternatively, the vertical picture can be derived from understanding the likely processes that have led to its formation. See Pain et al. (2001) for details of methods.

There are several geophysical techniques that help reveal the vertical dimension of regolith material distribution. Most notably, aeromagnetic imagery can identify buried palaeochannels containing maghemite. Maghemite generally forms near the surface as pea-sized nodules

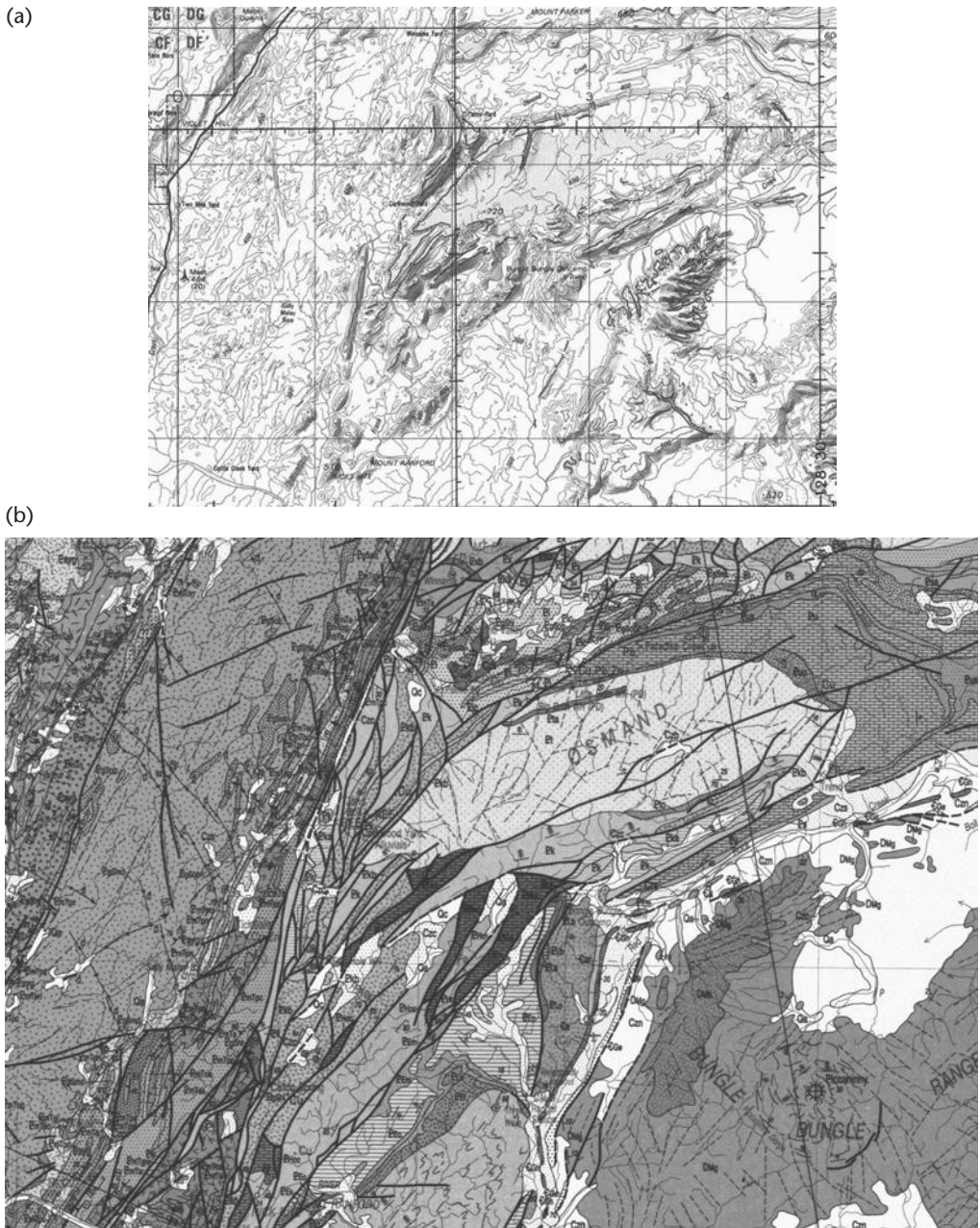


Figure 4.2 Extracts from the Dixon Range 1:250 000 (a) topographic and (b) geology sheets showing the close correlation between landscape and geology that can be noted at this scale. (The maps presented here are not at 1:250 000 scale).

and is easily transported and concentrated in alluvial systems, creating a useful magnetic signature. Electromagnetic (EM) surveys can sense regolith stratigraphy, but to calibrate the images generally, you need a log of the regolith. EM techniques also measure the conductivity of the regolith, and conductivity differences can help to decipher differences in regolith materials. Increasingly, this technique is also being used to map potentially saline groundwater

(e.g. Munday et al. 2004). Other useful geophysical methods for mapping regolith are described in Papp (2002).

Regolith data of limited coverage are available from Geoscience Australia. The Geological Surveys of Western Australia and Victoria also produce regolith maps. Regions of relative data concentration include Cape York, Broken Hill and the Eastern Goldfields of Western Australia.

There are many types of regolith maps. Early maps tried to show, at coarse scales, the distribution of weathering in Australia. More recently, coarse-scale maps showing regolith by genesis were compiled by the Bureau of Mineral Resources (now Geoscience Australia). Other coarse-scale maps of regolith types and regolith–landform relations are available for certain areas. Maps at such coarse scales are useful only for regional overviews.

Since the early 1990s, CSIRO in Western Australia has produced regolith–landform maps at several scales (usually detailed) based on contemporary or inferred past processes of regolith formation. Because they show Residual or relict parts of the landscape, Erosional parts and Depositional regions, they are known as RED maps. Some maps note secondary chemical regolith overprints (e.g. carbonate cementations). Because of the way the landscape is classified, these maps are much more interpretative than the Geoscience Australia maps. They are usually accompanied by detailed geochemistry and description of regolith materials. RED maps were compiled primarily to promote more successful mineral exploration by suggesting where ore-bodies in the bedrock are likely to be. As a result, they do not provide comprehensive detail of the distribution of the regolith. However, the CSIRO regolith data include vertical information because work was focused on where minerals were expected, at which point bore holes and pits were sunk. The data are in reports by CSIRO Division of Exploration and Mining, CRC LEME and AMIRA, and most easily found through the CRC LEME web page (CRC LEME 2004).

Regolith maps of various types are now commonly produced by state and territory geological agencies and Geoscience Australia. Some maps show detailed regolith data, including engineering or geotechnical engineering maps, morphostratigraphic maps and urban geological maps.

Regolith maps can provide detailed information on materials. They allow users to infer how materials behave under various uses, how water might penetrate, and how the minerals may react to wetting and drying; they also give insights into the behaviour and chemistry of groundwater. Such maps also provide details of the soil's parent material.

Hydrology and regolith

Almost invariably, water in landscapes moves within the regolith. Infiltrating rain affects soil weathering. Water chemistry changes with time as reactions with regolith and fresh rocks proceed. If water returns to the surface at springs, the quality of base flow in streams is affected. The regolith can be a major store of salts, including sodium chloride (NaCl). As water moves through the regolith it dissolves salts, carrying them through the landscape. In places, usually in the lower parts of landscapes, NaCl accumulates along with various other salts. For example, sometimes uranium salts accumulate and can be identified on radiometric images obtained on atmospherically still days.

Buried landscapes are important in controlling movements of groundwater in the regolith. In the Gilmore Project area (Lawrie et al. 2000) in the central west of New South Wales, aeromagnetic surveys clearly showed considerable variation in rock structure below what are now flat plains. Aerial electromagnetic and digital elevation data revealed a buried topography: a series of strike ridges with intervening basins. Ancient, and now buried, stream channels appear on the aeromagnetic images – apparent by their large magnetite content – and are seen to cut through the strike ridges as gorges. The buried gorges constrict groundwater drainage

from the upstream basin: groundwater ponded behind the ridges is highly conductive, whereas that downstream of the gorges is much less so.

If you find that information on geology and regolith is scarce – for example, only a 1:250 000 geology map and a few bores – then consider the above possibilities, paying particular attention to substrate topography and pathways of water movement.

Interpreting geological data for land resource survey

Soil parent materials

There have been several attempts to summarise geological rock names into a simpler classification, one that focuses on the inherent characteristics of rocks as soil parent materials.

The Parent Rock Code (Turvey 1987, Turner et al. 1990, Turvey et al. 1990) classifies rocks according to their dominant soil-forming potential. Table 4.2 classifies rocks into 12 parent rock classes that have pedological significance. Each class is further split into consolidated and unconsolidated subclasses, producing a total of 24 codes. The individual parent rock classes can be categorised by attributes that affect the nutrient and water regimes of soils derived from them (Table 4.2). Gray and Murphy (1999) have developed a more generalised parent-material classification, summarised in Table 4.3. Either classification can be used for land resource survey.

In many instances the relationship between rocks and soils is tenuous because the regolith is thick (perhaps 50 m or more), and as a result, the regolith largely determines the nature of the soil rather than of the rock beneath. For transported regolith, bedrock type may have its weathered products spread more widely than shown by its distribution on a geological map. Colluvial, alluvial and aeolian processes transport regolith, and can move it many tens of kilometres from its source. Consider these factors when working with surface materials and determine the significance of sediment redistribution (see *Chapter 5*).

Geomorphic relationships

Understanding the relations between geology and topography helps in resource survey. The easiest way to reach this understanding is to combine elevation data and boundaries of classes from geological maps as follows.

- Prepare representative two-dimensional cross-sections of the major topographic features with the finest-resolution landform data using an exaggerated elevation (ordinate), adding the geological boundaries and any geological structures (similar to the cross-sections on geological maps) – this can be done manually or digitally.
- Use a geographical information system (GIS) to ‘drape’ the geology over a digital elevation model and view the result in perspective.

Within the major geological map units, use topographical information to assess further structural information by looking for:

- distinctive streamline and drainage patterns (McDonald et al. 1990, p. 40, figure 4)
- orientation or patterns in hillcrests
- lineations
- nick points in streams or intersections of streams and major hillcrests/ridges
- planar surfaces
- discontinuities in contour pattern (e.g. orientation, intensity).

In addition, consult accompanying publications and explanatory notes prior to survey. They usually include locations of type sections, or major outcrops from which stratigraphy has

Table 4.2 A classification of rock types according to soil chemical and physical fertility relevant to *Pinus radiata*

Code		Parent rock	Consolidated/unconsolidated
00		Unspecified	
01	1	Carbonaceous Group	Coal, lignite, carbonaceous shale, torbanite (oil shale)
01	2		Peat
02	1	Quartzose Group	Chert, jasper, silcrete (greybilly), quartzite, quartz sandstone, quartz conglomerate
02	2		Quartz sands, quartz gravels, colluvium from 021
03	1	Sesquioxide Group	Iron ores, massive ferricrete (laterite), massive or pisolitic bauxite, ferruginous sandstone, ferruginous shale
03	2		Ferricrete (laterite or ironstone) gravel, bauxite gravel, ferruginous sands, glauconitic sands, saprolite and colluvium from 031
04	1	Calcareous Group	Marble, limestone, dolomite, travertine, calcarenite, calcrete, marl
04	2		Marl, shelly sands, coralline sands, colluvium from 041
05	1	Argillaceous Group	Slate, shale, claystone, siltstone, mudstone, lithic sandstones (graywacke)
05	2		Parna, clay-rich alluvium, silty alluvium, clay pedoderms, saprolite and colluvium from 051
06	1	Micaceous–Chloritic Group	Phyllite, schist, mica schist, green schist
06	2		Highly micaceous sands, saprolite and colluvium from 061
07	1	Feldspathic–Quartzose Group A – medium to coarse grain rocks	Aplite, granite, granophyre, pegmatite, granitic porphyry, granitic gneiss, adamellite, felspathic sandstone (arkose)
07	2		Saprolite and colluvium from 071
08	1	Feldspathic–Quartzose Group B – fine to medium-grained rocks	Rhyolite, micro-granite, ignimbrite, felsite, rhyolitic tuff
08	2		Rhyolitic ash, saprolite and colluvium from 081
09	1	Feldspathic–Micaceous Group	Granodiorite, quartz diorite, diorite, tonalite, lamprophyre
09	2		Saprolite and colluvium from 091
10	1	Feldspathic Group	Trachyte, syenite, monzonite, dacite, trachytic tuff
10	2		Trachytic ash, saprolite and colluvium from 101
11	1	Ferro-magnesium Group	Spillite, basalt, dolerite, diabase, andesite, gabbro, greenstone, teschenite, basic agglomerates, latite, amphibolite
11	2		Basic volcanic ash, saprolite and colluvium from 111
12	1	Magnesium-silicate Group	Serpentinite, dunite, peridotite, ultra-basic rocks
12	2		Talc, saprolite and colluvium from 121

The 3rd digit in the Parent Rock Code denotes whether the material is consolidated or unconsolidated (after Turvey 1987).

Table 4.3 Broad classification of soil parent materials for pedological purposes (Gray and Murphy 1999)

Parent material category	Silica (SiO ₂) content	Base content (Ca, Mg & Fe oxides)	Examples
Extremely siliceous	> 90%	Extremely low (~ <3%)	Quartz sands (beach, alluvial or aeolian), chert, quartzite, quartz sandstones, quartz veins (reefs) and silicified rocks (silcrete and silic hydrothermal alteration)
Highly siliceous	72–90%	Low (~ 3–7%)	Granite, rhyolite, adamellite, quartz sandstone, quartz siltstone and siliceous tuff
Transitional siliceous / intermediate	62–72%	Moderately low (~ 7–14%)	Granodiorite, dacite, trachyte, syenite, most lithic sandstones (graywacke), most argillaceous rocks (mudstone, claystone, shale, slate, phyllite and schist) and siliceous/intermediate tuff
Intermediate	52–62%	Moderate (generally 14–20%)	Monzonite, trachy-andesite, diorite, andesite, intermediate tuff, lithic sandstone (graywacke) and argillaceous rock
Mafic	45–52%	High (~ 20–30%)	Gabbro, dolerite, basalt and mafic tuff (uncommon)
Ultramafic	< 45%	Very high (~ >30%)	Serpentinite, dunite, peridotite, amphibolite, and tremolite–chlorite–talc schist
Calcareous	Low ^A	CaCO ₃ dominant, other bases variable	Limestone, dolomite, calcareous shale (marl) and calcareous sands
Alluvial	Variable ^A	Variable	Alluvium and estuarine mud
Organic	Low ^A	Organic matter dominant, bases variable	Peat, coal and humified vegetative matter
Sesquioxidic	Variable ^A	Variable, dominated by sesquioxides such as iron and aluminium	Ferricrete (laterite and ironstone), bauxite, and ferruginous sandstone

^A Character not defined by silica content.

been deciphered and analytical specimens collected. Visit these locations to familiarise yourself with the major rock types, their outcropping and the stratigraphic interpretation made by the geologists.

Use of geological units in sampling strategies

Major geological map units can be used for spatially stratifying a region prior to reconnaissance and for stratified random sampling (see *Chapter 20*). As field data are collected and collated, these initial geological units can be refined. They can eventually provide classes within which soil–landscape models (implicit or explicit) can be developed.

Linking geological data with soil and land attributes

Geological and regolith data can be used for predicting and interpreting land qualities such as erodibility.

Regolith stability

The risks of landslides and mass movement can be interpreted from combinations of regolith and terrain. Murphy et al. (1998) produced a Regolith Stability Classification to help assess erosion hazard in New South Wales State Forests. Geoscience Australia also produces information on landslide risk in relation to land attributes, including regolith (e.g. Granger et al. 2001).

Geochemical classifications

Several large databases of geochemical information cover the southeast of Australia including:

- Geoscience Australia ROCKCHEM database
- Australian National University, Geology Department (Dr Bruce Chappell) – Lachlan Fold Belt database

These databases focus on igneous (mostly plutonic) rocks and mineralised sites. There are fewer analyses of sedimentary rocks.

Geochemical data can be used for several purposes. Large granitic batholiths can be subdivided into plutons according to variations in major elements, trace elements and their ratios. They can also be used to calculate various chemical indices relating to potential soil fertility or erodibility, assuming that geochemistry of parent material influences soil chemistry. For example, the total phosphorus (diphosphorus pentoxide, $P_2O_5\%$) of the parent material places an upper limit on the natural soil's pool of total P. Leaching, erosion and any off-take in live-stock will, however, diminish the soil's total P. Fertility indices based on geochemical data can be used as surrogates for soil chemical data. Exercise caution, however, because sampling, especially on too small supports (see *Chapters 3 and 20*), creates more uncertainty for rock geochemistry than it does for soils.

Examples of indices include the following:

1. A useful index of potential soil fertility (*FI*) is the ratio of the base cation elements, calcium (Ca) and magnesium (Mg), and total phosphorus (P) to silicon (Si) (Equation 4.1):

$$FI = (CaO + MgO + 10 \times P_2O_5) / SiO_2 \quad (\text{Eqn 4.1})$$

This geochemical index is based on the assumptions that *FI*:

- increases with increasing P_2O_5
- increases as the base oxides of calcium, magnesium, potassium (K) and sodium (CaO, MgO, K_2O and Na_2O) increase
- decreases by dilution as the inert oxide (silicon dioxide, SiO_2) increases.

2. A stability index (*SI*) can be calculated in several ways, and a useful form is (Equation 4.2):

$$SI = (Fe_2O_3 + FeO) / (SiO_2 + Na_2O) \quad (\text{Eqn 4.2})$$

This index is based on assuming that *SI*:

- increases as ferro-magnesium minerals (iron(III) oxide, Fe_2O_3 ; iron(II) oxide, FeO; magnesium oxide, MgO; and manganese oxide, MnO) increase because sesquioxides provide cements and confer aggregate stability
- decreases as sodium oxide (Na_2O) increases because exchangeable sodium cation (Na^+) increases the potential for clay dispersion
- decreases by dilution as the inert oxide (silicon dioxide, SiO_2) increases.

Regolith attributes

The primary attributes for characterising regolith are described by Pain et al. (2000). There are many features in common with land resource survey. Greater emphasis is placed on the bedrock geology of materials and descriptions of regolith materials at the surface and deep within the profile (i.e. commonly tens of metres).

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Soil and landscape processes

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Introduction

This chapter reviews conceptual models of soil and landscape evolution, emphasising the soil component. It is restricted to qualitative models expressed through narratives, diagrams and sets of rules. These models are nearly always local in application and are based on more or less detailed field observations. Constructing and testing useful conceptual models of historic and contemporary processes is often difficult because field evidence is fragmentary and usually incomplete. Furthermore, it is easy to inadvertently confuse evidence with interpretation. In ideal circumstances, these conceptual models:

- explain the nature of materials at or near the Earth's surface
- explain the spatial distribution of these materials
- provide a basis for sampling and predicting soil and landscape properties
- indicate landscape dynamics and likely rates of processes (e.g. erosion, water movement, aeration, solute transport, acidification, nutrient movement)
- enhance assessment over that provided by simple inventory.

Soil and landscape evolution

Soil formation is intimately connected with other landscape processes relating to geology, climate, landform development, water movement, vegetation and fauna. Change occurs over an enormous range of scales in both time and space. Many interactions and feedbacks occur within and between the atmosphere, biosphere and geosphere. These relationships are highlighted in Jenny's (1941, 1980) five factors of soil formation: climate, organisms, relief, time and parent material. Refer to Birkeland (1999) for a full account.

There are various ways of conceptualising how landscapes and soils evolve. For convenience, a soil individual (see *Chapter 20*) within a toposequence is considered. The evolution of this soil individual occurs via a series of *additions*, *removals*, *transformations* and *translocations* of materials (Simonson 1959, Figure 5.1).

Various types of additions, removals, transformations and translocations can be distinguished. The more important for Australian conditions are listed in Table 5.1. Each type of addition, removal, transformation or translocation is associated with a set of more fundamental physical, chemical and biological processes. The surveyor needs to understand these processes to make reliable observations and interpretations. Standard texts on pedology that are relevant to Australian conditions include Paton et al. (1995), Birkeland (1999), McKenzie et al. (2004) and Van Breeman and Buurman (2002). Gray and Murphy (1999) provide a useful guide to the influence of parent material on soil distribution in Eastern Australia.

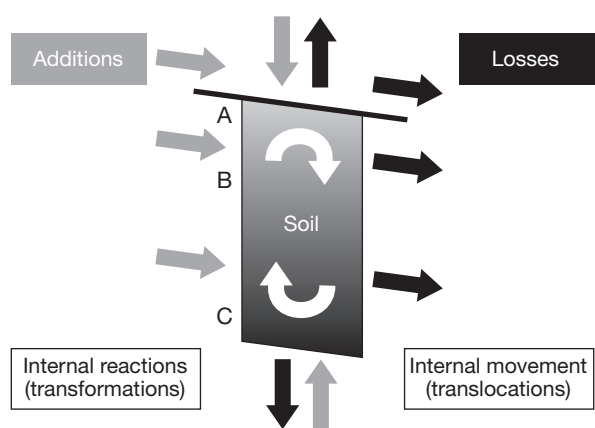


Figure 5.1 Model of soil formation based on additions, removals, transformations and translocations (after Simonson 1959).

Table 5.1 Major processes of addition, loss, transformation and translocation in Australian soils and their significance for mapping and land management.

Process	Description	Significance
References augment standard texts on soil science and pedology.		
Additions		
Hillslope deposition	Sedimentation caused by overland flow and deposition of coarse bedload and finer colloids (Moss and Walker 1978)	A primary control on sequences of soil types, from crests to valley bottoms
Alluvial deposition	Sedimentation caused by flooding	Energy of flooding controls sediment character (i.e. clay versus sand) and overall soil properties
Aeolian deposition	Sedimentation of sands and silts near the source area and finer material at greater distances	Obvious control on soil properties in desert dunefields but also a major sediment and nutrient source across large parts of the globe
Plant litter	Organic material deposited at the land surface or within the profile by roots	Primary energy source for life in the soil, and a driver of weathering and soil formation
Substrate weathering	Breakdown of primary minerals results in the release of nutrients and other compounds (Taylor and Eggleton 2001)	Source of mineral nutrients for plant growth and life in the soil
Soluble salts	Additions either through rainfall, dry deposition, or introduction via groundwater	Significant source of nutrients, and in some regions, troublesome salts
Losses		
Erosion	Removal of soil by water and wind from the land surface and sometimes deeper layers (e.g. gully erosion) (Edwards and Zierholz 2000)	A primary control on sequences of soil types, from crests to valley bottoms. Accelerated erosion reduces the soil's nutrient supplies and available water capacity. Sediment and nutrient delivery to waterways affects water quality
Solution loss	Various ions in solution are leached from the profile	Intensity of leaching influences degree of weathering and fertility in the long run

Process	Description	Significance
Volatilisation	Compounds produced by various soil processes (especially burning) are lost to the atmosphere as a gas (e.g. carbon dioxide, nitrous oxide)	A cause of long-term nutrient depletion
Transformations		
New mineral formation	Various minerals, especially clay minerals, are created from either soluble ions or changes to existing minerals (Dixon and Schulze 2002)	Creation of charged surfaces allows nutrients to be retained and exchanged with the soil solution – essential for the plant-nutrient supply system
Organic matter decomposition	Leaf litter, plant roots, manure and dead organisms are broken down by microorganisms to eventually produce carbon dioxide and humus	Fundamental component of the carbon cycle and therefore necessary for life on earth. Various forms of organic matter provide charged surfaces (see <i>New mineral formation</i>) and nutrients for plants. Controls soil colour to varying degrees
Iron	Oxidation and reduction. Dissolution and precipitation of iron	Resulting patterns of soil colour and iron compounds are useful diagnostics for the soil–water regime (e.g. seasonal waterlogging) (Vepraskas 1992, Bigham et al. 2002)
Translocations		
Clay	Movement in association with percolating water, or as a result of soil organism activity (e.g. by earthworms, ants or termites) (Chittleborough 1992, Paton et al. 1995, Phillips 2004)	Can enhance or prevent the development of contrasting A and B horizons (Vepraskas 1992, Bigham et al. 2002)
Iron	In its dissolved state, iron can move to create zones that are depleted or sites of precipitation and concentration	Resulting patterns of soil colour and iron compounds are useful diagnostics for the soil–water regime (Vepraskas 1992, Bigham et al. 2002)
Organic matter, iron and aluminium	Movement in Podzols and other light-textured soils results in depleted bleached horizons (A2) and accumulations produce distinctive Bh and Bs horizons	Nutrient reserves are often very small and B horizons can impede drainage. Soils are sensitive to disturbance (e.g. Thompson 1981, 1983, Walker et al. 1981)
Soluble salts	Movement of ions in the soil solution – largely controlled by the leaching intensity of the environment	Accumulations of some soluble salts in the soil profile can prevent plant growth. Can also lead to the formation of dispersive clays and a small non-limiting water range
Carbonate	As above, with controls on precipitation being affected by carbon dioxide concentration	Useful diagnostic for the degree of leaching
Bioturbation	Movement of materials within the profile caused by plants and animals	Incorporation of organic matter into soil. Can enhance or prevent the development of contrasting A and B horizons
Shrinking and swelling	Movement of materials within the profile and development of gilgai microtopography	Gives rise to distinctive soils that pose challenges for soil measurement, land management and engineering

Which particular process dominates and its rate of action are determined by both external factors (e.g. climate) and internal chemical responses. Despite this, some generalisations on rates can still be made (Yaalon 1971; Birkeland 1999; Chadwick and Chorover 2001). Soil properties that change rapidly (1–100 years) respond to external forcing factors and they include organic matter content, soluble salt distribution and formation or obliteration of mottles. Examples of properties that change slowly (100–1000 years) are horizons of clay, iron-humus or carbonate accumulation. Soil features that change over longer periods (10^4 – 10^6 years) include large accumulations of secondary phases such as carbonates or silica, or profound depletions of soluble minerals that leave behind a nearly inert residuum of iron oxides and kaolinite.

Broad-scale processes of landscape evolution set the context for the processes of soil formation listed in Table 5.1. These include aspects of plate tectonics, structural geology, climate change, plant ecology and hydrology – see Summerfield (1991) for an excellent overview.

Environmental change in ancient landscapes

The previous section outlined the basic sets of soil processes controlling formation and function. The next step is to understand how these processes have operated through time. To a large extent, soils record their past (Yaalon 1983). Soil properties and patterns in the landscape can arise from processes that operated under very different conditions from those of today. Surveyors therefore need to understand the extraordinary environmental history of our continent.

In most regions, an appreciation of events from at least the start of the Paleogene subperiod is essential. In some areas, an understanding of events and processes from even more distant times will be required (e.g. Gale 1992).

The major events that have governed the direction of landscape evolution and soil formation in most regions are emphasised as follows.

1. The Permian period (298–251 million years ago, mya) is significant because much of Australia was covered by a great ice sheet (Beckmann 1983; Ollier 1986) and it gave a fresh start to landform and soil evolution.
2. The continent had become a flat land by the Cretaceous (141–65 mya). During the Cretaceous, shallow seas spread across much of the continent. Land remained in the west, north-west and east. The marine sediments of the Cretaceous covered large areas (e.g. Gulf lands of North Queensland) so that when the seas receded they left the continent even flatter.
3. Most tectonic movements since that time have consisted of warpings, some vertical uplifts and minor faulting. Most notable was the rise of the eastern highlands and the Great Escarpment (Ollier 1982).
4. Many of the intricacies and patterns of soil formation evident in the landscape today have their origins in the interactions between the subdued landscapes from the end of the Cretaceous and the increasingly variable climates of more recent times.
5. For most of the last 100 million years, until 2 mya, temperatures exceeded those of today. During this period, and particularly from 150 mya to 50 mya, there is little evidence for continental ice sheets. As Australia drifted northwards after separation from Gondwana, the vegetation of the continent was dominated by rainforest species and most of the continent experienced a humid climate (Barlow 1994; Martin 1994). The tectonic stability of the period, together with the humid climate, resulted in widespread and strong weathering. Intact soils or remnants formed during this period still cover large parts of Australia.

6. The climate became cooler during the Paleogene and Neogene. The cooling during this time gave way to dramatic oscillations of global climate throughout the Pleistocene. The early Pleistocene saw a transition to fluctuating climates, with a trend to increased aridity. The shift to greater aridity in southern Australia occurred 350–700 thousand years ago whereas in northern Australia it was earlier (Pillans and Bourman 2001)
7. Successions of glacial and interglacial periods caused important changes in windiness, sea level and the balance between rainfall and evaporation. Most of our understanding for these times comes from between the last interglacial (120 000 years ago) and the last glacial maximum (18 000 years ago). During the initial phase of this period, the climate in southern Australia was cool and moist – the latter as a result of slower evaporation rates rather than increased precipitation. Streamflows and sediment loads were much greater, and a major phase of alluvial deposition occurred – most notably in the Riverine Plain of southeast Australia (Bowler 1986, 2002).
8. Nearer to the last glacial maximum, conditions became cool and dry, with average rainfall about half that of today. One consequence of increased temperature gradients between the Equator and Poles was an increase in windiness. Wind, in association with the drier climate, caused major phases of dune building in Australia and an increase in dust deposition around the globe (Wasson and Clark 1988; McTainsh and Leys 1993; Simonson 1995).
9. Globally, the increase in ice volume caused a sea level drop of about 120 m. This exposed large areas of continental shelf in the Great Australian Bight, and land bridges from the continent extended to Tasmania and to Papua New Guinea. The southern exposures are thought to have provided a source for the deflation of carbonates that were subsequently deposited across large areas of southern Australia (Crocker 1946; Wasson and Clark 1988).
10. The enormous swings of climate during the Pleistocene had a dramatic impact on ecosystems. Some of these changes have undoubtedly had a major impact on soils – for example, the relatively recent dominance of genera including *Eucalyptus* and *Corymbia*, and the contraction in abundance of *Casuarina* and *Allocasuarina* (Hope 1994; Martin 1994). Vegetation changes accompanied the drier conditions in the glacial period and wetter ones during interglacial times. These features – along with an increase in burning (Bowman 1998) that decreased organic matter levels – probably reduced soil physical and chemical fertility across large areas of Australia.
11. Whereas only a small area was directly affected by Pleistocene glaciation – 15 km² on the mainland and 1000 km² in Tasmania (Bowler 1986; Barrows et al. 2001) – a much larger area was affected by periglacial processes and these provided large supplies of material for streams to transport.
12. Since Aboriginal settlement, the continent has experienced the loss of the Australian megafauna, increased fire frequency, changed vegetation, and subsequent disruptions to patterns and rates of nutrient cycling. These are sure to have changed soil conditions, but the extent and degree are not known.

The Holocene period marks a transition to present conditions. Sea levels were similar to now and many coastal landforms and soils assumed their current state. A reduction in stream-flow and bedload transport in the rivers of the Riverine Plain incised the landscape (Bowler et al. 1986). The area of eucalypt forest and rainforest also increased (Hope 1994).

The impact of European land use has been dramatic. Accelerated erosion and sedimentation, increased leaching, acidification, widespread decline in organic matter, contamination and compaction have modified many soils. Despite their recent occurrence, in many landscapes it is difficult to attribute changes in soil properties to particular events.

Developing an understanding of landscape processes during survey

Balancing pedology, edaphology and geography

During survey the challenge is to translate our understanding of pedogenesis, past environments and landscape evolution into a form that improves mapping and land evaluation. Few surveys will have the time and resources necessary to improve our understanding of landscape evolution, although surveyors who can acquire this understanding are usually more effective in assessing the qualities and potential of land.

Most surveys need to strike a balance between:

- a *pedological* focus that considers soil materials, principles of occurrence and processes of origin
- a *geographical* focus that recognises patterns of soil variation and aims to map and interpret features in relation to land use
- an *edaphological* focus that considers soil conditions of significance to the growth and life-economy of plants (Butler 1958).

Finding this balance is an art as illustrated by the following scenario. A land resource surveyor is commissioned to survey a region to determine its suitability for new introductions of arable crops, pastures and trees. The job must be done in 18 months. Limits for soil properties affecting the growth of the plants are ill defined (e.g. susceptibility to water logging, potential toxicities and nutrient deficiencies). The surveyor is also faced with a complex landscape born of deep weathering, subsequent stripping, mobilisation of stored salts and aeolian deposition. An understanding of all these processes is necessary to answer questions relating to edaphology (e.g. will salinity be a problem?) and geography (where are the good quality soils formed from aeolian deposits?). Trade-offs are needed between the edaphic, pedological and geographical objectives:

- The sampling plan for developing a reliable model of landscape processes will differ to the strategy for mapping (see *Chapter 18*). For example, sites with good stratigraphic sequences will be sought (e.g. exposures in gullies and cuttings) and investment in several deep cores, supported by dating and mineralogical studies, may be desired (see *Chapter 17*). However, the geographical focus will place greater emphasis on evenly distributed sampling across the area.
- Even if the edaphic properties were well defined, the cost of direct measurement of the soil physical and nutritional properties may be prohibitive. It has been standard practice to assume that soil properties with pedological significance (particularly readily determined morphological properties) are well correlated with properties having edaphic significance. This is a good first approximation but be aware that relationships between standard soil morphology and more relevant soil properties are sometimes complex and weak (MacArthur et al. 1966; Webster and Butler 1976; Butler and Hubble 1977; McKenzie and MacLeod 1989).
- If a conventional survey is undertaken and land units are mapped, then the geographical criteria used for defining boundaries might not correspond to soil distinctions of relevance to plant growth. In this example, practicality dictates that mapping must rely on readily observed features of the landscape (geology, landform, vegetation, air-photo pattern).

The edaphic, pedological and geographical orientation is often confused in the presentation of results – most notably in classification. Choosing differentiae, selecting 'taxonomic

1. View soils as mantles
2. Define stratigraphic units (pedoderms)
3. Identify boundaries between pedoderms
4. Define sedimentary systems within pedoderms
5. Trace the provenance of materials
6. Determine textural trends within pedoderms
7. Detect patterns of wetness within pedoderms

Figure 5.2 Major steps in the development of a local model of soil and landscape evolution (after Butler 1982).

chops' (Butler 1980), and maximising correlation with mappable entities or genetic concepts has generated much unproductive debate. Make sure you understand the client's needs and provide information they need. In most cases, they will want to know about options for land management so emphasise these. With this context in mind, the discussion proceeds to the method for developing a local model of soil and landscape evolution.

Developing local models of soil and landscape evolution

Our guidelines for developing local models of soil and landscape evolution are based on Butler (1982)¹ and they emphasise environmental history, provenance of materials, the sedimentary system and hydrology (Figure 5.2). These are set within the broader framework provided by Jenny's functional factorial approach. This approach has been implemented to a large extent in the soil-landscape mapping program in New South Wales (e.g. Atkinson 1993; Chapman and Atkinson 2000).

View soils as mantles

Understanding soil and landscape evolution requires a three-dimensional view of the landscape and its change through time. Soil needs to be viewed as a mantle rather than as a two-dimensional profile set within a land unit (see *Chapter 2*). The soil that mantles the land has formed on regolith or from the parent rock directly. The geometric or *stratigraphic* relationships between soil mantles provide evidence from which we can deduce soil history. In many Australian landscapes, the resulting knowledge of soil and landscape evolution provides a good basis for mapping and ensures a more complete appreciation of landscape processes.

Define stratigraphic units and use the pedoderm concept

Central to stratigraphic work are the concepts of the *paleosol* and *pedoderm*. A paleosol is any soil formed on any landscape in the past; it may be in a buried, exhumed or relict landscape position (Beckmann 1984). Brewer et al. (1970) defined the pedoderm as:

a mappable unit mantle of soil, entire or partially truncated, at the earth's surface or partially or wholly buried, which has physical characteristics and stratigraphic relationships that permit its consistent recognition and mapping.

¹ Butler's outline of a 'new system for soil studies' is difficult to understand unless the reader is familiar with his lifetime's work. Hence, the highly condensed synthesis presented here goes only part way to increasing potential understanding of Butler's work.

A pedoderm represents one period in which soil formation has taken place (Beckmann 1984) and this period may span several changes in environmental conditions. Soil properties vary within a pedoderm because of different soil-forming processes relating to the sedimentary system, provenance of materials, textural sorting and patterns of wetness – these aspects are discussed in the following sections. A pedoderm can be subdivided into horizons but pedologically related horizons should not be considered as separate pedoderms (Brewer et al. 1970).

Identify boundaries between pedoderms

Field investigators need to recognise pedoderms and then identify boundaries between units. This requires:

- establishing that specific soil layers are independent of each other (i.e. they have not formed by transformations or translocations)
- recognising buried soils
- locating the edges of pedoderms.

These are not trivial tasks and they require a breadth of field skills. Examples of field studies are noted by Butler (1982). Practical guidelines on soil stratigraphy are provided by Daniels et al. (1971) and Daniels and Hammer (1992).

Recognise sedimentary systems within pedoderms

Apart from soils that develop *in situ* through the weathering of fresh rock, most form in sediments of some type. These mineral materials are produced under regimes of erosion, transport, sorting and deposition. Various geomorphological agents and modes of geomorphological activity are involved (Butler 1982, Speight 1990). The energy of the agents (e.g. gravity, precipitation, stream flow, wind, ice, standing water, biological agents, internal forces) usually determine the grading, size, sorting and shape of individual particles, and this in turn exerts a strong control on soil development. The surveyor needs to pay particular attention to the nature of the sand fraction during profile description: Butler (1982) recommends close inspection of the sand component during profile description – this component is washed out of a hand specimen in the field.

Use field observations and remotely sensed imagery to stratify pedoderms into units with different sedimentary systems. A provisional stratification is produced at the start of an investigation and is progressively refined as better field information becomes available.

Trace the provenance of materials within pedoderms

The importance of provenance varies with landscape. In some parts of Australia, knowledge of the substrate geology provides a good basis for predicting soil distribution (e.g. Gray and Murphy 1999). In other areas, the provenance of the soil parent material is harder to identify and the link to soil profile form is difficult to discern. The utility of geological mapping also varies (see *Chapter 2*) because rock types are often defined on criteria apart from lithology. For example, chronostratigraphic distinctions might bear little relation to mineralogical and grain-size factors that determine the products of weathering.

Despite these complications, always attempt to trace the provenance of materials within pedoderms. Airborne gamma radiometric spectroscopy is nearly always of assistance.

Determine textural trends within pedoderms

The energy of geomorphological and pedological processes produces predictable textural trends within a pedoderm. Terrain analysis (see *Chapter 4*) is a central tool for predicting patterns within pedoderms. Remember that disparate patterns of texture variation can occur

in contrasting sedimentary systems (e.g. alluvial, erosional, colluvial, aeolian), and terrain variables useful for predicting soil distribution will be highly conditional.

Detect patterns of wetness within pedodermis

The remaining phase of model development addresses the patterns of soil variation that relate directly to water redistribution and drainage. The former depends heavily on landform while the latter is also affected by the texture of sediments and pedogenesis. High-resolution digital elevation models are invaluable for this phase.

Other considerations

The approach outlined above aims to go beyond explanations of soil formation strictly in terms of the factors outlined by Jenny (1941, 1980). Our approach acknowledges the value of the functional factorial approach but it also emphasises the materials and history of soils in the local landscape. It is more consistent with a geomorphological view of the landscape because of the emphasis on sedimentary systems, stratigraphy and the potential for dating.

Minimal attention has been given here to the role of vegetation, soil organisms and their coevolution with soils. In some landscapes, the history of coevolution is starting to be unravelled (e.g. Walker et al. 1981; Adams 1996; Pate et al. 2001) and it can sometimes provide a powerful basis for predicting soil distribution.

Benefits of understanding soil and landscape processes

An understanding of soil and landscape processes improves assessment without providing clear evidence. Surveys can be undertaken from a strongly geographical view with only a minimal understanding of landscape evolution and soil formation. This works well in simple landscapes where soil distribution is orderly (see *Chapter 3*). For example, land-system survey and soil-landscape mapping can be executed in a strongly geographical mode with no reference to landscape evolution. Another common example is land resource mapping that relies heavily on analysis of remotely sensed imagery (e.g. airborne geophysics, multispectral reflectance remote sensing) with little field checking.

Proponents of these approaches would argue that investing heavily in developing a reliable understanding of landscape processes is possible only with an enormous effort in the field and laboratory. Without this investment, it is all too easy to develop an erroneous model. Indeed, the debates over landscape evolution would suggest that most models are wrong and that resolution of debates between some competing models is unlikely. Examples of such debates include those over climates associated with prior streams (Butler 1960 versus Langford-Smith 1960), uplift of the eastern highlands of Australia (Bishop 1988) and formation of ferricrete (see Bourman 1993).

There is a balance to be struck. Surveys should describe the soil and land resources of a given area in an explicit, consistent and repeatable manner (see *Chapter 2, Recommendations*). Inferences about landscape processes should be based on clear evidence. Too often, soil and landscape morphology (*form*) are confused with interpretations of *process*.

It may be useful to remember that 'all models are wrong but some are more useful than others.' Although there are cases where interpretations of landscape processes have been based on erroneous models, the resulting predictions of landscape processes are not completely wrong. However, a more accurate model will provide many advantages, not only in improving survey efficiency but, more importantly, in supplying the insights necessary for good land management.

Generalised conceptual models for Australian soil provinces

A fundamental issue for conceptual models of landscape processes and pedogenesis is the degree to which models developed for one location can be transferred to other apparently similar landscapes. There are no simple guidelines, but the following should be borne in mind.

- The contemporary landscape derives from diverse environmental variables and soil interactions over a very long time. There should, therefore, not necessarily be any similarity between locations. A rudimentary review of the geologic, geomorphic, climatic and ecological processes operating in most landscapes suggests complexity rather than simplicity.
- Various workers (e.g. Butler 1964) conclude that, at best, models could be expected to have local applicability. However, some geomorphical processes such as deep weathering and regional aeolian activity (e.g. dust deposition) have left a widespread imprint. Likewise, the climatic oscillations of the Pleistocene operated at regional scales (some operated more broadly) so the imprints should be at a similar scale.

It is well beyond the scope of this chapter to consider the many local models for soil and landscape evolution across Australia. CSIRO (1983) is a primary source. The references and case studies in Taylor and Eggleton (2001) and McKenzie et al. (2004) should also be consulted. Webb (1994) provides a useful overview for New Zealand. Many survey reports published by state and territory agencies describe local models for soil and landscape evolution.

A major challenge will be to organise existing models within a logical spatial framework and develop an explicit method for specifying the environmental and geographical range over which models can be applied. The hierarchy of land units in the Australian Soil Resource Information System (ASRIS 2006) provides a logical starting point. Preparation of systematic narratives, diagrams and sets of rules are required. Specification of these models at Levels 3 and 4 within ASRIS are likely to be most useful.

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Digital terrain analysis

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Introduction

Our capacity to analyse landform quantitatively has changed land resource survey profoundly. This chapter provides a review of digital terrain analysis. For more details, the reader should consult Wilson and Gallant (2000) and Hengl and Reuter (2007).

Key concepts

What is a digital elevation model?

A *digital elevation model* (DEM) is a computer representation of the land surface. It represents not only heights but also the shape of the land, the direction of water flow, the curvature of the surface. Shape is inferred from differences between neighbouring heights. DEMs come in three forms: grid, *triangulated irregular networks* (TINs) and contour-element networks.

- A grid is a set of point elevations arranged in a regular pattern (usually oriented N–S and E–W) at equal spacing in both directions. Grids are the simplest arrangements of heights for computer processing and they are represented as a two-dimensional array with the location of each point implicit in the array index.
- A TIN is a set of irregularly spaced points that form triangular elements so that the topology of connection is defined. Its main advantage is adaptivity – the ability to use more points where the surface is more complex – but it requires storing the coordinates of cell points as well as their elevations.
- A contour-element network is represented as strings of points forming contours, with lines (usually straight lines) between the contours delineating irregularly shaped units of land surface. Their main advantage is that they implicitly represent the hydrological connectivity of the land surface, but they are difficult to generate.

Although all three forms of DEM have enjoyed popularity at times since the mid-1980s, regular-grid DEMs are now the most common by far. For some applications TINs are still used but not generally in land resource survey. Contour-based DEMs are used only for special purposes such as dynamic hydrologic modelling. Generally, all new DEMs are regular grids, and most current software for handling terrain data works on grids. Other forms of DEM are possible, and it may be that feature-based representations (see Gallant and Hutchinson 1996) will supplant or complement grid DEMs in the future. Intrinsically multiscaled storage techniques that allow data to be efficiently extracted at different resolutions are also appearing.

Interpreting a grid DEM

A grid DEM does not exactly represent the real surface. Nor is it necessarily true that somewhere within each pixel (or grid cell) the elevation will exactly match the DEM value, nor that the DEM value represents the average elevation in the pixel. It is also misleading to think of a DEM as a tessellation of flat squares. It is better to see a DEM as a set of point heights from a surface that approximates the real surface. The shape of the surface *between* the points is undefined and is not usually of interest, but can be explicitly extracted by a mathematical interpolation (Gallant 2001). The shape of the surface *at* each point is the domain of terrain analysis, as described later (see *Terrain attributes*).

Some of the confusion between point and cell values arises from the visual representation of grids as pixels or cells. This gives the mistaken impression that a grid represents a continuously varying surface as a set of square cells of constant value with abrupt changes at the edge of each cell, especially when the view is zoomed in so the DEM cells are readily visible. It would be more accurate to represent the surface as points (single pixels on the display device) with blank areas between them when zoomed in, but this is more difficult to display.

The inclusion of the word 'model' in the term DEM is for good reason – the data only approximate the structure of the real surface. The fidelity of that representation depends on the resolution of the DEM, the source data from which it is created, the nature of the landscape being represented and the purpose for which the DEM is being used. A DEM at 25-m resolution, for example, might not be able to represent the details of surface flow paths but might still capture the spatial structure of subsurface redistribution of water.

It is useful in some instances to distinguish between two types of DEM. A *digital terrain model* (DTM) represents the natural surface and a *digital surface model* (DSM) includes features such as buildings, vegetation and bridges. The distinction becomes more important with the increasing use of data derived from imagery or direct measurement such as scanning laser altimetry.

What does terrain analysis do?

Terrain analysis is the means by which elevation data are converted into quantitative information about landform, thereby encapsulating the relationships between landform and other interesting things such as soils, water availability and vegetation.

To classify landforms and produce integrated surveys, early terrain analysts (e.g. Speight 1974, 1977) used manual techniques for analysis of contour maps, aerial photography and field observation. Such methods are good at distinguishing meaningful patterns in the landscape but suffer several major drawbacks: inconsistency between mappers, lack of explicitness in how the land units are defined, consumption of much time, and difficulty in relating spatial patterns to soil physical and chemical properties (since these do not follow the same patterns in the landscape).

Modern, automated terrain analysis based on digital terrain data has almost the exact opposite set of characteristics. It is quantitative, explicit and rapid due to increases in computing power and storage capacity. However, delineation of meaningful units is still a problem. The technology is immature, providing useful methods but not yet a set of robust, generally applicable solutions. The multiple spatial patterns that can be derived from terrain data correlate with some soil physical and chemical properties, but none provides a complete explanation and the relationships change from place to place.

Each new effort at terrain analysis aims to elucidate spatial patterns in natural systems and involves collection of sample data and the building of statistical models. The nature of those models changes from place to place, and interpretation in terms of physical processes can be

difficult. The threshold, where we have developed models in enough different areas to understand where particular models are applicable, or even what constrains the limits of applicability, has not been reached. A key challenge over the next decade or two is to develop more explicit understanding of how soil properties depend on environmental variables (landform, climate, parent material) and to understand the domains where those relationships are applicable. This will require synthesis of statistical studies and a review of the biophysical bases for relationships.

Another approach is to use combinations of terrain variables, possibly augmented with other environmental variables when they appear to represent genuine landscape variations (e.g. topographic wetness index, multi-resolution valley bottom flatness index –see *Terrain attributes*). These representations can be developed from physical principles and sometimes from intuition based on observation ('how can we represent what I see in the landscape?'). These methods are more likely to be transferable, or at least have clearly defined limits of applicability, as well as having a clear interpretation, but their validity in explaining the observed patterns has to be clearly established (unlike the statistical models where statistical validity is intrinsic to the process of model construction).

Managing terrain data and generating DEMs

Synopsis of digital elevation model generation

In the past, users created their own DEMs from data. It is now more usual for them to buy already processed DEMs from data providers. Producing a DEM typically involves four steps:

1. acquiring data
2. converting, pre-processing and checking data as necessary, including projection and format conversion
3. constructing a DEM from the data
4. checking the DEM, correcting errors in the data, and reconstructing as required.

There may be several iterations of checking and fixing before the DEM is satisfactory.

Data acquisition

The data for DEMs are usually derived from one or more of:

- topographic contours, spot heights and streamlines
- soft photogrammetry from aerial photographs or satellite remote sensing
- direct measurements: laser altimetry (one to a few dollars per hectare, depending on size of area and intensity of data), synthetic aperture radar (airborne and satellite), altimetry from geophysical surveys, and land-based survey using differential global positioning systems.

Data sources associated with routine topographic mapping tend to be cheapest (e.g. a few hundred dollars per map sheet for contours, spot heights, streamlines). The cost for airborne and satellite data has declined substantially and may well become the most economic source of data in the near future.

Data preparation

Use the appropriate datum (e.g. GDA94) and projection (see *Chapter 16, Navigating and georeferencing*). Cleaning data is time-consuming – see Wilson and Gallant (2000) for details, especially in relation to the orienting of streamlines.

DEM production

Interpolation of sparse data

DEMs are often generated from scattered data in the form of contours (from topographic maps) or scattered spot heights (from GPS or similar surveys). Drainage lines and small numbers of spot heights frequently supplement the contour data. Because the source data are sparse relative to the final DEM resolution, the interpolation of a surface from the scattered data is a major determinant of the quality of the final product.

There are many interpolation products available, and each results in surfaces of differing quality. Algorithms range from simple inverse-distance weighting through to more sophisticated methods such as kriging or splines. Each method has its advantages and disadvantages, but the quick and easy methods generally produce unsatisfactory results. This is particularly true for contour data: these data are dense along contours but the relatively wide spaces between contours makes interpolation difficult. More importantly, contours encode shape as well as elevation, and a good interpolation algorithm will use this shape information. Supplementary information on drainage lines also provides important information on shape. Good algorithms for interpolation also make use of the fact that topographic surfaces generally drain and are thus free of sinks (points that are lower than all adjacent points).

The ANUDEM software (Hutchinson 2004) is recommended for interpolation of sparse data. It infers ridge and valley lines from contour inflections to maintain those structures, uses drainage direction information from streamlines, and automatically enforces drainage.

Smoothing of dense data

With dense source data, there is little need for sophisticated interpolation to fill the gaps between data points. However, the raw data from lidar, radar or direct photogrammetry contain intrinsic noise or variation from point to point that is not part of the terrain surface. Depending on the method of acquisition and the quality of the post-processing, these sources also include to a varying degree non-terrain features such as trees and buildings. All dense data, therefore, require some form of smoothing or post-processing to produce a DEM suitable for terrain analysis.

The first level of processing is to separate ground and non-ground points. This is a standard processing step for lidar data and can take advantage of its ability to measure multiple-returns (reflections from the laser source), allowing it to pick out the latest (furthest and hence lowest) return. This also allows measurement of tree canopy height and sometimes density. Processing to remove solid structures such as buildings is a much more difficult task because it requires classification of surface features. Such capabilities are still under development and, until reliable methods are available, these features must be identified and removed manually.

Checking

Once a DEM has been produced or acquired, how does one ensure that it reliably represents the terrain surface? Several techniques are available to assess DEM quality quickly. Hutchinson and Gallant (2000) provide further details and examples.

Comparing derived contours with source

Contours can be derived from the DEM at the same interval as source contours and the two sets of contours visually compared. Interpolation invariably involves some smoothing, so that the lines will not overlap exactly (especially at sharp bends on ridges and in valleys).

This comparison will easily identify any systematic errors in position or elevation, which will be apparent from the offsets in the contour lines. Errors in the source data – such as mislabelled

contour heights, incorrect spot heights, or reversed stream lines – also produce easily identifiable discrepancies in the derived contours.

Visual inspection of derived contours is useful even if no source data contours are available for comparison, since they often reveal shortcomings in the quality of the DEM.

Shaded relief images

A shaded relief image of a DEM provides a visual representation of the terrain surface that is easy to interpret and is also sensitive to anomalies in the DEM. The image is usually derived using an illumination angle of 30 degrees above the horizon directed from the northwest (about 300 degrees azimuth), although in the Northern Hemisphere it is common practice to use illumination from the southwest.

The errors induced by integer resolution are readily visible in a shaded relief image. Differences in the scales of source data giving rise to different surface textures are also apparent, as are edge-matching problems in the source data.

Spurious sinks

Sinks or local depressions in the surface are frequently an indication of problems in a DEM (except where natural depressions occur). Sinks may be caused by incorrect or insufficient data, or by an interpolation technique that does not enforce surface drainage.

Quantitative checking

More detailed quantitative checking of a DEM can be done at well-chosen field sites with, for example, differential carrier phase-based GPS receivers (see *Chapter 16*). These provide positions and heights to an accuracy of a few centimetres. Suitable sites for checking are well-defined peaks or bends in drainage lines to determine positional error and broad flat areas for checking elevation error.

This form of checking can assure the user that the DEM has no systematic errors in position and elevation, but provides no assurance of the shape accuracy of the DEM unless many measurements are made. Derived contours and shaded relief images are better for assessing quality of shape representation in the DEM.

Availability of DEM data

National coverage

At the national scale, a DEM covering the entire Australian continent at 9-second (about 250 m) resolution is available from Geoscience Australia (2006). This DEM is derived from source data at cartographic scales of 1:100 000 and 1:250 000 from spot heights, selected contour points and oriented streamlines. These data are useful for analysis at coarser scales and across broad areas but cannot support analysis at the hillslope scale since most hillslopes are smaller than a grid cell.

In 2004, the Shuttle Radar Topographic Mission data became available (SRTM 2004), providing near-global DEM coverage at 3-second (about 90 m) resolution. These data were obtained in 2000 by synthetic aperture radar equipment mounted on the Space Shuttle. They can provide more detailed topographic data than the 9-second DEM, particularly in low-relief landscapes where the source data for the 9-second DEM are sparse. However, the SRTM data appear to contain elevation errors induced by dense vegetation (e.g. riparian woodlands) and structures (e.g. fence lines). These errors limit their utility for quantitative analysis. Methods to remove the unwanted features are being developed.

DEMs based on satellite imagery are also becoming available for large areas of the world including Australia. These are usually derived from overlapping pairs of images by automatic

techniques for image correlation. While heights can be estimated from overlapping images from separate passes, the difference in surface patterns between images taken at different times can compromise the correlation. The ASTER instrument carried aboard the Terra satellite avoids this problem by taking two images in each pass, one vertically and one at an angle – DEMs are produced at 30 m resolution. At the time of writing, ASTER DEMs are available free of charge from the US Geological Survey Land Processes Distributed Active Archive Center (ASTER data products 2006). DEMs derived by stereo correlation of images include vegetation and structures above the ground surface, so further processing is usually required to derive actual ground heights. Other satellite systems providing derived DEMs include SPOT-5 (at 10 m resolution), Ikonos (1 m) and QuickBird (1 m or better).

State and territory data

Most states and territories have mapping programs that produce topographic maps at 1:25 000 scale or thereabouts, at least where land use is moderately intensive. These data can be used to derive DEMs of 20 m to 25 m resolution. Soft photogrammetry has been used across southwest Western Australia to produce DEMs directly from aerial photographs at a similar or finer scale.

These data are generally at a suitable scale for landscape analysis and are fairly reliable at capturing the shape of individual hillslopes and landform elements.

Site-specific data

Higher resolution data are often collected at individual sites for specific purposes. This often involves detailed geographical positioning system (GPS) survey, although laser altimetry now offers similar accuracy over much larger areas.

How do you look after a DEM?

Several forms of data manipulation create problems with digital elevation data. The resampling and projecting of grid DEMs almost always introduces sinks into the surface. When projecting grid DEMs, the locations of spot heights in the resulting DEM do not exactly match those in the source DEM, so interpolation is used to construct the value at that point. While this can be accurate, a valley floor may be raised sufficiently to create sink points.

Similar consequences arise from resampling to a coarser resolution because of skipped points or from resampling to a grid that does not overlay the source grid. Resampling to a finer spacing that coincides with the original grid is harmless but usually pointless because it reveals no additional surface detail. Sometimes it may be necessary to match another data source. The terrain attributes derived from such a resampled DEM may contain evidence of the resampling.

Sinks create problems for some derivatives. They interrupt the calculation of flow accumulation downslope (see *Terrain attributes*) and lead to incorrect contributing-area values; they need special handling to restore flow connectivity. The techniques commonly used to do this are not very sophisticated and produce flat areas in which flow accumulation fails to respect the underlying topography. This then produces errors when combining terrain indices such as contributing area and slope.

It is generally safe to project vector source data, since each vertex retains its position relative to others nearby. This is the best way of obtaining a DEM in a different projection from the supplied data (i.e. contours, streamlines, spot heights). However, if you only have a DEM and it has to be in another projection, there is no choice but to project it and deal with the associated problems.

Floating-point data can be inadvertently converted to integers. This often happens in data transfers between agencies or between software systems. The reduction of precision as a result of such conversions disrupts the continuity of surface shape in DEMs. It is commonly defended on

the grounds that the DEM would not be accurate to better than 1 m, which is generally true, so nothing is being lost, which is not true. Because shape is represented as the difference in elevation between adjacent points, forcing all heights to integer values distorts those relationships defining shape. This is particularly severe in low-relief areas where the distance between points differing in elevation by more than 1 m can be substantial. In these areas integer precision produces a surface where slope appears to be zero in most places but occasionally steep where the DEM jumps by 1 m, while attributes such as aspect and curvature are undefined in most places. Smaller increments of 0.1 m or 0.01 m reduce these problems but do not eliminate them. Single-precision floating-point data have about seven digits of precision so even at Australia's highest point, elevation differences of less than 1 mm can be resolved. The simple message is that good quality DEMs are never stored as integers.

Terrain analysis methods

Key variables

With the exception of rainfall and temperature, elevation is not in itself strongly correlated with many environmental attributes relevant in land resource survey. Most of the links between elevation and land attributes are related to the shape of the landscape. These include:

- slope as a measure of rates of material transport including water flow
- aspect as a measure of exposure to wind, rain and sun
- plan curvature as a measure of convergence and divergence of flow
- contributing area or specific catchment area as a measure of the area of land delivering water to a part of the landscape
- percentile as an index of relative position within the local landscape.

These shape factors are captured by primary topographic attributes derived directly from the DEM. Further secondary attributes can be derived from combinations of primary attributes or with additional non-terrain information, and are generally designed to be closely related to specific processes, such as:

- the topographic wetness index (the ratio of specific catchment area to slope), which is a measure of relative soil wetness
- the stream power index (the product of specific catchment area and slope), which is a measure of the ability of surface flow to transport sediment
- shortwave radiation, the amount of radiation reaching the surface as modified by atmospheric affects, location, time of year, and slope and aspect of the land surface. This is a measurable quantity, not just a relative index, and the calculations are closer to a physically based model than a terrain index.

Scale issues

Scale and resolution exert a significant influence on the quality of terrain analysis results and the way in which the terrain attributes can be used. In general, higher-resolution (smaller spacing between DEM points) and finer-scale source data provide a more accurate representation of terrain shape and hence more reliable predictors of soil properties. Higher-resolution data are also more expensive than coarser data, so a compromise between quality and cost is inevitable.

Terrain attributes can be systematically biased by changes in resolution or scale of source data. Moore et al. (1991) showed the effects of different resolution on slope and contributing area. Slope generally decreases with coarser resolution: Gallant (2001) showed that slope

derived from the 9-second DEM of Australia was about 50% less than the average slope over the area of each 9-second cell derived from 25 m DEMs.

Because of the different scales at which various processes are organised in the landscape, a terrain attribute may have different interpretations at different scales. For example, slope at 20 m resolution is closely connected with gravity-driven processes, and so is likely to be a useful predictor of soil attributes connected with movement of materials down the slope. At 1 km resolution, slope is more closely related to broad-scale relief, and therefore is likely to have a different relationship to soil. Gessler (1996) demonstrated that useful predictions of soil properties (e.g. solum thickness) could be obtained from terrain attributes at resolutions of up to 40 m, but coarser resolutions provided poor predictions.

Terrain attributes

Several terrain attributes can be computed from a DEM, some of which use well-established algorithms. Most of the following attributes are described in more detail in Wilson and Gallant (2000), together with descriptions of the algorithms.

Many terrain attributes can be computed within raster GIS packages, such as Arc/Info and Grass. Stand-alone programs are also available, such as the TAPES suite of programs originally developed by Ian Moore and described in Wilson and Gallant (2000).

Terrain attributes are calculated from grid DEMs from differences in elevation between adjacent grid points. Most calculations use the eight points surrounding a given grid node, and such numerical approximations to mathematical derivatives are termed *finite differences*.

Slope

Slope, S , measures the rate of change of elevation in the direction of steepest descent. Slope is the means by which gravity induces the flow of water and other materials, so it is of great significance in gradational processes of landscape evolution and soil development (Speight 1990).

Slope is usually measured either as a percentage or in degrees. Note that slope can exceed 100% where slope angles are greater than 45 degrees.

Slope is usually calculated using finite differences, but can also be calculated from only the single adjacent point that has the steepest descent from the current point. The steepest descent method is, in general, less accurate but remains useful for calculating slope in channels when the influence of surrounding hillslopes needs to be excluded.

Aspect

Aspect, ψ , is the orientation of the line of steepest descent and, together with slope, measures the exposure of a surface to wind, rain and solar radiation. It is usually measured in degrees clockwise from north, the same as a compass bearing.

Aspect is calculated by finite differences. An alternative, from direction of steepest descent, can also be derived, but is not widely used as a measure of aspect *per se* but is used to support contributing area calculations (see *Contributing area and specific catchment area*).

Curvatures

Curvature attributes measure several types of curvature of the land surface, and are calculated by finite differences. The two curvatures most commonly measured in terrain analysis are plan (or contour) curvature, K_c , the horizontal curvature of a contour line, and profile curvature, K_p , the vertical curvature of a flow line perpendicular to a contour line. Contour curvature measures convergence and divergence of flow, while profile curvature measures increasing or decreasing slope along the flow path. They are signed quantities, with the usual convention that positive curvatures indicate convex curves – this corresponds to divergent flow paths for contour curvature and increasing slope for profile curvature.

The units of curvature are radians per metre, which is the change in orientation that results from travelling 1 m along the respective line. Because these values are usually much less than 1, they are commonly multiplied by 100. They can also be expressed as degrees per metre.

Contributing area and specific catchment area

Upslope contributing area, A , is the area above a given length of contour that contributes flow across the contour. Specific catchment area, a , is the contributing area A divided by the length of contour, l , across which that area discharges.

Specific catchment area is a surrogate for discharge: if runoff is generated uniformly at a given depth, the discharge per unit length of contour is the depth multiplied by specific catchment area. When calculated for a nearly constant flow width (as is the case with grids) the patterns of contributing area and specific catchment area are essentially the same.

Contributing area may be expressed in square metres, hectares (10^4 m^2) or square kilometres (10^6 m^2). Specific catchment area has units of metres.

One computes contributing area by adding cell areas, or fractions of cell areas, to downslope cells. If this process is commenced at hilltops where there are no contributing cells, the values can be propagated downslope across the entire DEM until every value has a contributing area. This is the one case where DEM grids are considered as cells with area rather than as grids of points.

In general, flow directions will not coincide exactly with one of the eight directions to adjacent cells in the grid, so there is scope for choosing how flow out of a cell is distributed to downslope cells. The result is a variety of different algorithms for calculating contributing area. Distributing flow to downslope cells on a square grid is complicated by the problem of flow across corners of cells. No existing method is completely satisfactory in this respect, so new algorithms continue to be developed.

Single flow direction (D8) method

The simplest approach is the single flow direction method, commonly called D8, which directs all flow out of a grid cell to the single downslope neighbour with the steepest descent. Although simple and efficient, this method has serious drawbacks. The most important is that it cannot account for flow dispersion in divergent (ridge-like) areas. Its use is not recommended, although it is adequate for delineating catchment boundaries and defining channels.

Multiple flow direction slope-weighted (FD8) method

The D8 method can be substantially improved by distributing flow to all downslope neighbours in proportion to their slope. This method is called the multiple flow direction or FD8 method, and allows flow dispersion in divergent areas. Its main drawback is that it produces too much dispersion, with flow being dispersed to multiple downslope neighbours even in convergent areas such as valley bottoms. One solution is to switch to the single flow direction method when the contributing area exceeds a threshold. A more sophisticated approach is to raise slope to a power larger than unity when computing the proportions of flow to downslope neighbours, which has the effect of directing more flow to the steepest downslope neighbour. Increasing the exponent as contributing area increases results in a progressive change from the fully dispersed method to the single direction method.

The D-infinity method

An alternative to the slope-weighted approach is to use a variant of aspect to apportion flow to only one or two directions (see Tarboton 1997). This method greatly reduces the problem of excessive dispersion.

Stream tube (DEMON) method

This more sophisticated approach constructs flow lines from each corner of the cell and continues them downslope, following aspect at all places, until a sink or the edge of the DEM is reached. The lines defined by the DEMON algorithm do not have to respect cell boundaries and so provide a much better representation of the surface flow paths than cell-to-cell transfer. The area of each cell is distributed to all downslope cells along the flow path. This method provides an accurate representation of dispersion in divergent areas and avoids dispersion in convergent areas, but the algorithm is very inefficient because it traverses the full flow-path down from every cell.

Choice of contributing area algorithm

Provided its inefficiency can be tolerated, the DEMON algorithm is the preferred method because of its fidelity to landscape shape. If a more efficient algorithm is needed, use the D-infinity or FD8 methods. Avoid the single direction D8 method except where catchment areas are the only consideration and the spatial patterns of contributing area are not required.

Depressions and flat areas

All contributing area algorithms depend on finding downslope flow paths, so any grid point that has no lower neighbours represents a barrier to the algorithm. Such a point is called a sink, and it has an associated depression comprising all surrounding points that drain to the sink and are lower than the lowest outflow for the sink. In some cases a sink is a true representation of the landscape, such as a sinkhole in karst terrain, but more often it is a defect of the DEM and flow-routing needs to continue out of the depression. This is usually achieved by filling the depression: raising the elevation of cells within the depression to match the lowest outflow point. The flow-routing algorithms then route the flow across the flat areas by constructing flow directions backwards from the outflow point.

One problem with this approach is that the flow paths within the filled depression do not respect the underlying topography, so the location of large contributing area values within the depression will not necessarily correspond with the centre of a valley. This can cause undesirable effects where contributing area is combined with (for example) slope, resulting in combinations of large slope from hillslopes with a large contributing area that should have been in the valley floor.

Ideally, any DEM used for computing contributing area should be free of depressions, and a DEM containing spurious depressions should ideally be re-created after correction of the source data responsible for the depression. Where this is not possible, the sinks can be filled. An alternative method of restoring drainage connectivity involves burning-in the streams: elevations along the mapped streamlines are reduced so there is continuous drainage down the stream lines. This approach is best avoided, as it can still leave depressions in areas not directly drained by streams and it severely distorts slopes and other shape attributes of the surface.

Flow width

For the calculation of specific catchment area the contour length, l , is typically assumed to be equal to the grid resolution (cell size), but this raises some problems of logical consistency with flow across corners of cells.

Different contributing area algorithms use slightly different flow widths. The D8 method uses h for flow in cardinal directions and $\sqrt{2}h$ for flow in diagonal directions. The DEMON method uses a continuously varying width based on aspect, but with the same range as D8 (h to $\sqrt{2}h$). The flow widths for the FD8 and D-infinity methods are more difficult to define. The

current TAPES-G implementation uses a flow width ranging from h to $4h$ depending on the distribution of flow weights (Gallant and Wilson 2001).

Flow-path length

Flow-path length is sometimes used as an indicator of position within a catchment or hillslope.

Flow-path length is the maximum distance along a flow path from the catchment boundary to a given point in the DEM. It is computed in a manner similar to that for contributing area but accumulating the distances across cells, rather than areas, and using only the largest value from incoming cells, rather than the sum of all values.

Downslope attributes

In some applications it is the shape of the landscape downslope of each point (rather than upslope) that is of particular interest. The main application is the control of soil water by specific dispersal area – the area to which a unit length of contour drains (Speight 1980).

By inverting the DEM, the algorithms for computing contributing area and flow-path length can be used to compute dispersal areas and lengths. Because negative elevation values can have specific meanings in some algorithms, the inversion is best achieved by subtraction of the DEM from a constant value larger than the greatest elevation in the DEM. Sinks in the inverted DEM correspond to peaks in the landscape that are generally real, so sinks should not be filled when computing dispersal areas.

Upslope averages of terrain attributes

For processes connected with the accumulation and dispersal of materials across the surface it can be argued that the average characteristics within the contributing area of a site may be as significant as the characteristics at that site. The mean value of terrain attributes within the contributing area may then be used as site variables.

Contextual terrain attributes

All the attributes described to this point rely on shape as defined by immediately adjacent grid points. In some instances it makes sense to consider the characteristics of the area surrounding a site considerably further away than the adjacent grid nodes. For example, a small rise in a valley might be better considered as part of the valley floor than as a hilltop, because the processes influencing it are dominated by its low position relative to the surrounding landscape rather than its high position relative to the immediate surroundings.

Some terrain attributes can be computed based on elevations within a circle of defined radius. The main difficulty with this type of analysis is the choice of radius. The best choice of radius is generally the size of the average hillslope length in the area of analysis.

Mean and standard deviation

Standard deviation of elevation within circles provides a measure of the variation of the landscape height, or relief.

The mean elevation within circles provides a smoothed version of the DEM. This is mostly useful in comparing site elevations to the mean of the surrounding elevation (see *Difference from mean*).

Difference from mean

The difference between site height and the mean elevation in the surrounding landscape provides a useful measure of landscape position. Large positive values mean the site is much

higher than its surroundings and is likely to be exposed and well drained, while sites much lower than their surroundings are likely to be more protected and kept wetter by drainage from the higher areas. This concept is used in the FLAG analysis method (see *FLAG Upness*).

Elevation percentile

Elevation percentile provides a ranking of the site compared with its surroundings. It is calculated as the proportion of nodes within the circles that are lower than the sites. Values near zero indicate locations low in the local landscape, while values near 100% indicate a location high in the local landscape. Because these values do not depend on the actual height differences they can be used as the basis for classifying landscape position. The drawback is that, in regions of low relief, the results are unreasonably sensitive to small height variations. This may be overcome by inclusion of a measure of vertical error, so that height differences less than a specified threshold are not considered significant.

Solar radiation modelling and the Prescott Index

Incident solar radiation is an important driver of the water balance and thermal environment. The topographic influences on radiation as a result of shading, slope and aspect can be readily determined by terrain analysis. With the addition of information on cloudiness and atmospheric transmission, a reasonably accurate estimate of incoming radiation can be calculated. The SRAD program from the TAPES package computes incoming short-wave radiation based on these variables (Wilson and Gallant 2000). Additional variables, specifying surface albedo and the moderation of surface temperature by vegetation, enable SRAD to compute incoming long-wave radiation and outgoing radiation, and hence net radiation.

The Prescott Index (Prescott 1948) provides a crude index of the water balance based on precipitation and evaporation. Net radiation from SRAD can be used to derive potential evaporation (incorporating the effects of terrain orientation), and the pattern of annual precipitation can be obtained with the ESOCIM program (Hutchinson 1989). The resulting map of the Prescott Index provides a useful estimate of profile leaching suitable for predicting soil properties in specific environments (McKenzie and Ryan 1999, McKenzie et al. 2000).

Landscape position

Landscape position is a measure of the location of a site within the context of the surrounding landscape. There are various categorical measures and Speight's (1990) morphological types are widely used in Australia. Speight's classification uses terms such as crests, upper slopes, lower slopes, depressions and flats that have fairly clear definitions. The translation of such schemes to automated classification is difficult, partly because computer-based methods are much more limited than human interpretations and partly because the definitions are clear but fuzzy. For example, Speight's definition of a crest is a 'landform element that stands above all, or almost all points in the adjacent terrain'. Precise definition of 'almost all' and 'adjacent' are necessary to implement such a scheme in a computer program.

Several attempts at automated landscape position classification have been attempted, none of which are entirely successful. Skidmore (1990) defined ridges and streams, then divided the areas between them into upper, middle and lower slopes based on distances to the nearest ridge and stream. This simple scheme is reasonably effective but suffers in some places from misidentification of the stream or ridge to which a location's landscape position should be referenced. Coops et al. (1998) improved on the forgoing procedure by constructing flow lines joining ridges and valleys, similar to figure 2a in Speight (1990), and dividing the slope profile into one, two or three segments depending on its geometric complexity. Although this approach

is more sophisticated than earlier methods, it suffers from some artefacts as a result of each slope profile being processed separately (so that adjacent profiles can have different slope classifications).

A different approach to classification of landscape position is to use numerical classification (e.g. Scott and Austin 1971, Speight 1976, Ventura and Irvin 2000). These methods are effective at delineating different landforms. However, the delineated units do not necessarily relate to established landform classifications, and it is not clear how well they would perform outside the domain in which they were developed.

Some simple terrain attributes such as elevation percentile or FLAG (see *FLAG Upness*) can also be used as indicators of landscape position. These attributes have a continuous range of values rather than particular classes, although they can also be classified with ranges of values.

Further developments are needed because of the large amount of existing survey information that is georeferenced only by landscape position. Without a map of landscape positions, spatial predictions based on these measurements are severely hindered.

FLAG Upness

The Fuzzy Landscape Analysis GIS (FLAG) terrain analysis method (Roberts et al. 1997) was designed to predict areas of dryland salinity from terrain data. It uses methods from fuzzy set theory to combine the patterns derived from three primary terrain attributes: 'lowness', 'concavity' and 'upness'. Lowness is based on difference from mean elevation in a defined region and concavity is based on plan curvature. Upness is a generalised contributing area that includes all DEM cells that are connected to the target cell by a downhill path, regardless of whether surface catchment boundaries are crossed. This measure of contributing area is intended to reflect the influence of uphill areas on hydraulic head, so is more connected with subsurface flow pathways than the surface flow paths represented by the classical contributing area. Like contributing area, it has units of area (m^2 , ha or km^2) although the FLAG method rescales this to the range 0 to 1 for any analysis area.

The FLAG analysis method has been demonstrated to correlate with discharge areas and catchment salinity (Dowling et al. 2003). The methods may also have utility for deriving land units and predicting soil properties.

Multiresolution terrain attributes

As noted earlier, patterns in the landscape can be observed at a range of scales. Terrain analysis approaches that operate at multiple scales can capture these multiscale patterns.

The first of these methods to be developed is the multiresolution valley bottom flatness index (MrVBF), which identifies valley floors as areas that are both relatively flat and locally low (Gallant and Dowling 2003). Flatness is measured as slope transformed to the range 0 to 1 based on a threshold, so that slopes much greater than the threshold have a flatness near 0 and slopes much less than the threshold have a flatness near 1. Local lowness is measured as a percentile, inverted so that small percentile values give a lowness near 1. The method is applied at multiple resolutions by progressive smoothing and coarsening of the DEM while simultaneously reducing the slope threshold. The resulting index takes on values less than 0.5 in areas that are not valley floors (ridges, hilltops, hillslopes) and larger values for progressively broader and flatter valley bottoms.

The MrVBF index can be used to support delineation of land units by its depiction of valley floors and different terrain textures. It also appears to have promise as a predictor of soil thickness and other properties as a result of the connection between valley floors and sediment deposition (Gallant and Dowling 2003, McKenzie et al. 2003).

Use of terrain analysis in land survey

Terrain analysis is central to land resource survey. In conventional survey, terrain analysis was done by air photo interpretation (Speight 1977) although evidence and interpretation were often mixed. Terrain analysis using DEMs is explicit and it encourages evidence and interpretation to be presented unambiguously. The methods have an important role in the following:

- description of landform (e.g. slope maps, statistics)
- providing a basis for stratification of sampling sites
- generating predictor variables for soil–landscape models
- improved visualisation and communication (e.g. shaded relief images).

Identifying landscape units

The identification of land units at various scales (see *Chapter 3*, Table 3.2) is an important application of terrain data. While quantitative methods for land resource survey emphasise the continuous nature of landscape variation, classification into tracts is still needed for many applications. Automated terrain analysis has not yet reached the degree of refinement where relevant and interpretable land units can be reliably derived, but there are several approaches that provide useful delineations of land unit tracts.

Units of uniform slope are useful in landform mapping and can be derived from DEMs. Simple classification of slope produces a fragmented map, but units similar to those derived by manual aerial photograph interpretation can be produced by aggregation algorithms.

Coops et al. (1998) describe a method for deriving landform elements (Speight 1990) from DEMs using a combination of several techniques. Crests and depressions are identified from plan and profile curvature and elevation percentile, while the remaining areas are identified as slopes. Within the slope areas, flow lines are constructed, and the profile form of these lines analysed to delineate upper, middle and lower slope units.

The MrVBF can be used to delineate valley floor units corresponding to areas of alluvial and colluvial deposits (Gallant and Dowling 2003). The different values of the index correspond to different scales of flat valley floors. Another approach to automated delineation of land units is to combine terrain attributes by clustering methods. This method requires training in manually delineated data.

Stratification

Terrain variables in combination with other environmental variables are useful for defining strata in stratified-random or multistage random sampling. They also provide a basis for planning purposive-sampling strategies (see *Chapters 18 and 20*) again through stratifying the study area and providing a means to ensure the full range of environments (e.g. terrain $\times$ geology $\times$ vegetation $\times$ land use) has been sampled. To illustrate the distribution of field sites, our advice is to use summary tables of terrain classes and sample numbers.

Soil–landscape models

The most significant role for terrain analysis in quantitative survey is through the provision of explanatory variables in soil–landscape models – see McKenzie et al. (2000) for a review. To date, most terrain variables used in soil–landscape modelling relate to humid environments with a reasonable degree of relief (> 10 m), and a predominance of erosional processes. Terrain variables such as MRVBF are well suited to low relief depositional environments. The potential exists to develop suites of terrain variables that capture patterns generated by most geomorphic agents (e.g. gravity, precipitation, stream flow, wind, ice, standing waves, volcanism, earth movements). These terrain variables will need to work across scales and incorporate information

beyond the hillslope and neighbouring depositional zone (e.g. through the use of stream patterns, lineaments, other structures).

Where is terrain analysis likely to be helpful?

Terrain analysis has generally been developed in landscapes of medium to high relief. There the influence of terrain on surface processes – primarily through control of water flow and radiation regime – is clear. Common relationships include:

- prevalence of wetter conditions in lower parts of the landscape caused by drainage through either the regolith or fractured bedrock
- deeper soils on slopes facing away from the sun (southern slopes in Australia) due to lower evaporative demand resulting in denser vegetation and more soil-forming activity (for chemical, biological, and erosion-protecting reasons)
- deeper, and sometimes more nutrient-rich soils in lower parts of the landscape as a result of downslope sediment transport and trapping in riparian zones.

In these medium to high relief landscapes, the terrain attributes that commonly prove predictive of soil properties are:

- slope
- specific catchment area
- plan curvature
- radiation measures
- aspect
- topographic wetness index
- stream power index.

These terrain attributes all respond to local shape and depend on the reliability of elevation differences between adjacent cells. The attributes connected with water flow also depend on the assumption that the direction of water flow follows the terrain surface, which is generally valid in hilly areas.

In low relief landscapes the situation is less clear, at least at first. These landscapes are often characterised by depressions, poorly organised surface drainage systems, flooding and ground-water systems (e.g. discharge zones). In such cases, the use of surface topography as an indicator of water movement is problematic. The difficulties are compounded where the DEM is derived from standard contour mapping in low relief areas. In the worst cases there may be only one or two contours on a map sheet, supported by scattered spot heights and some drainage lines.

Even very subtle surface topography can have a profound influence on soil properties and natural vegetation. This is especially evident across the nearly flat riverine plains of eastern Australia. For example, McKenzie and Austin (1993) detected large variations in soil properties related to small variations in local relief; they considered that reliable spatial prediction would be possible if terrain data could detect vertical changes of 0.3 m over hundreds of metres. Such terrain data can now be generated by lidar.

In low relief and arid regions, terrain attributes suited to erosional landscapes in humid environments are generally inappropriate. Local surface curvatures (plan, profile) are often unduly affected by irregularities in the elevation data, and so are unreliable indicators of surface process. Contributing area is not a reliable indicator of water availability or even flow propagation, as it is based on surface flow directions without regard to the height differences involved. Differences of only millimetres still count as downhill in contributing-area calculations. In reality, surface flow may be only significant during flood conditions when local flow direction is strongly influenced by hydrodynamics and essentially ignores the subtle topographic variations.

Local relative elevation is probably more useful (e.g. riverine plains example above), if only as an indicator of height above a shallow groundwater system. Depressions in many parts of Australia have accumulated salts, either now or in the past, and are often sodic and impermeable as a consequence.

In low relief landscapes, terrain attributes that are responsive to the organisation of the landscape at broader scales appear to be more appropriate than those that rely on differences in height between adjacent cells. The MrVBF index is such an attribute – it identifies valley bottoms at both fine and broad scales by analysing the DEM at a range of resolutions, progressively smoothing and coarsening the DEM to make broader-scale features apparent.

The most significant limitations to applications of terrain analysis in low relief areas are the lack of sufficiently precise terrain data and a lack of experience in applying it. The need is not for finer spatial resolution (25 m grain is just as good here as elsewhere) but for better representation of subtle surface shapes. As suggested earlier, direct methods of acquiring terrain data (laser or radar altimetry, SAR, soft photogrammetry) are promising, although the error of the data must be sufficiently small and avoid non-terrain heights.

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Hydrology

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Introduction

Many challenges in natural resource management centre on hydrology. A good understanding of hydrology leads to better quality surveys of land resources because many aspects of soil formation and landscape evolution are controlled by hydrological processes. Land resource survey, in turn, has the potential to improve analyses of landscape hydrology by providing an integrating framework and primary data to support estimates of infiltration, water storage, deep drainage, groundwater flow, stream flow and water quality.

This chapter contains a broad overview of hydrological processes including an account of the hydrological significance of soil features commonly encountered during survey. Major classes of hydrological models are described along with their data needs. Land resource surveys can make a major contribution to hydrology in this regard by providing primary data across a range of scales.

Hydrological processes

Virtually all water enters the land phase of the hydrological cycle as precipitation. Soil, landform, vegetation and climate then control its fate and it affects both vegetation and flow in streams and groundwater. The pathways by which water moves through the landscape and returns to the atmosphere are known as the land phase of the hydrological cycle (Figure 7.1).

Before describing the components of the hydrological cycle and the properties affecting them, especially soil properties, some fundamental soil hydraulic properties are introduced.

Some fundamental soil hydraulic properties

Soil water potential

Soil water has potential energy, referred to as *water potential*, which determines the state and drives movement of water in soil. Water moves along potential gradients from where potential energy is high to where it is low. The water potential is taken to be zero at a 'free' water surface. Thus, a soil that is completely saturated has zero water potential at the height corresponding to the free water surface. In an unsaturated soil, water potential is negative. The total soil water potential is the sum of three components:

1. The *gravitational potential* is simply the height above a fixed datum. Above this datum, gravitational potential is positive and below it is negative.
2. The *matric potential* occurs as a result of the mutual attraction between water and soil particles. Water is held within soil pores by a negative potential (or suction). As the soil dries, water is extracted most easily from the large pores so that the largest pores empty first followed by successively smaller ones. As progressively smaller pores empty, the

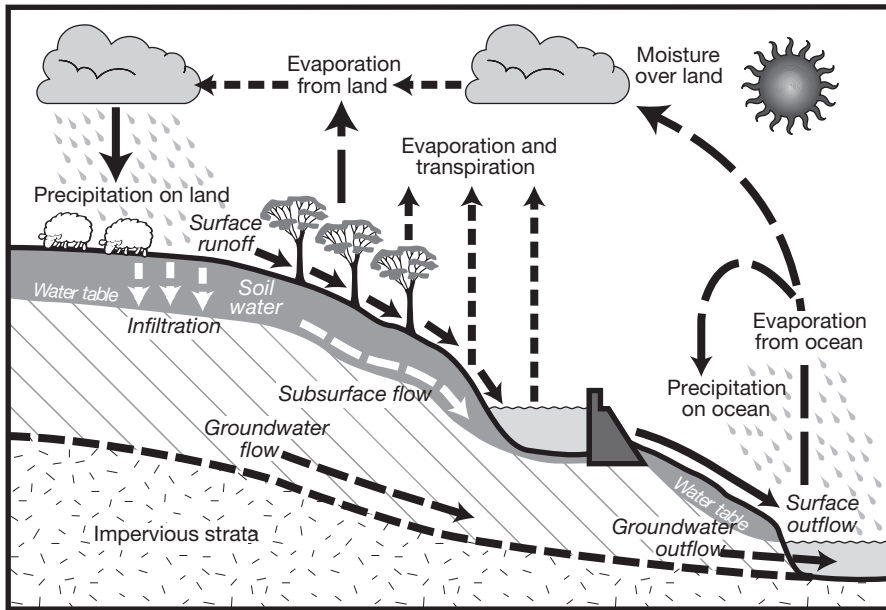


Figure 7.1 The hydrological cycle.

matric potential becomes increasingly negative. The smaller the pore, the more negative the potential it exerts.

3. The *osmotic potential* is created by dissolved salts and becomes more negative the greater the salt concentration. Water moves into zones with high salt concentration.

An extra component, the *overburden potential*, is present in soils that shrink and swell. Soil water potential is well described in soil physics texts (e.g. Jury et al. 1991; Marshall et al. 1996; Hillel 1998).

Soil water characteristic

The *soil water characteristic*, $\theta(\psi)$, is the relation between the soil's volumetric water content, θ , and matric potential, ψ . The soil water characteristic is a fundamental soil property that affects both the equilibrium water content and flow of water in soil. It is a necessary input for many computer models of the soil water balance. The amount of water retained in soil at large matric potentials (0 to -100 kPa) depends mainly on capillarity and pore size distribution. Soil macrostructure strongly affects the soil water characteristic over this range. At more negative potentials, water retention is controlled mainly by adsorptive forces and is influenced by the specific surface area and charge density.

The soil water characteristic is usually determined by the progressive drying of a saturated specimen. However, the soil water characteristic exhibits *hysteresis* because the curve obtained on wetting the soil is different to that from drying it (e.g. Hillel 1998).

Hydraulic conductivity

Hydraulic conductivity, K , is a measure of how fast water can move through soil. Specifically, it is the rate when the potential gradient is unity. Water movement decreases rapidly with decreasing pore size. Therefore, although smaller pores exert greater suction, they also have the smallest hydraulic conductivity. The $K(\psi)$ curve relates K to matric potential and hence to

the soil water characteristic. $K(\psi)$ is time-consuming to measure so normally only the saturated conductivity, K_s , or near-saturated conductivity are measured.

Precipitation

Precipitation includes rainfall, snowfall, hail and sleet. Snow processes are not covered here. Estimates of precipitation – including the amount, rate, duration and distribution in space and time – are critical inputs into water balance models and other hydrological tools used in water resource management. Uncertainty in input data such as precipitation translates to uncertainty in model predictions. Error in quantifying precipitation comes through error in point measurement and uncertainty in converting point-measurement to estimates of areal precipitation. Sources of error in point measurements include wind effects, water splash, systematic instrument errors such as under-recording with tipping-bucket gauges during heavy rainfall, and instrument malfunction. Dingman (1994) quotes typical errors of 3% to 30% for long term data and as high as 75% for individual storms. Errors are far larger when precipitation is as snow. Reported precipitation data should not be accepted uncritically.

Hydrological analysis often requires precipitation over an area, such as a water catchment, rather than at a point. Dingman (1994) reviewed the different methods for predicting the spatial pattern of precipitation from point data. Geostatistical methods (see *Chapter 23*) performed best in a variety of situations because they are based on the spatial correlation structure of the precipitation in the region of application. They have the additional advantage of providing estimates of uncertainty. Systematic spatial effects, such as orography leading to high rainfall at high elevations in mountainous areas, can be important in determining spatial patterns of precipitation and may not be captured by monitoring networks.

The Bureau of Meteorology provides weather, climate and hydrological services. Precipitation and other climate data are available from the websites of the Bureau (Bureau of Meteorology 2006) and Queensland Department of Natural Resources and Water (NR&M Enhanced Meteorological Datasets 2006). Together these agencies have delivered two useful data resources – the Patched Point Dataset (PPD) and the Data Drill (Jeffrey et al. 2001). Both data sets provide continuous daily climate data, suitable for use in computer models. The Data Drill provides estimates of daily weather since 1957 on a 0.05 degree grid (about 5 km) across the Australian continent by interpolating the Bureau of Meteorology's station records, using splining and kriging techniques. The data provided are all synthetic. Data accuracy is low in areas where (a) station density is low in absolute terms, and (b) station density is low relative to climate gradients (i.e. close to the coast, in areas of topographic complexity). Users should check if the accuracy of the interpolated surfaces is appropriate for their application, by comparison with observational point data. The Data Drill is delivered as an email from the Queensland Department of Natural Resources and Mines.

The Patched Point Dataset uses original Bureau of Meteorology measurements for about 4600 meteorological stations, and interpolated data are used to fill ('patch') gaps in the observational record. It is typically used when more accurate data are needed for analysis or simulation.

Interception

In any vegetated landscape, part of the precipitation is intercepted by the leaves and stems of the vegetation. This water may either be evaporated, drip from the leaves or flow down the plant stems to the soil surface. In forested systems, interception and subsequent evaporation can account for up to several tens of percentage of the total precipitation, although this may replace

transpiration losses to an extent (Dingman 1994). In forests and woodlands in particular, interception significantly reduces the amount of water reaching the soil surface, and can lead to very high spatial variability in the rate at which water reaches the surface and hence the rate at which it is available for infiltration. Hydrological models typically account for interception by either removing the initial few millimetres of a rainfall event or by temporarily storing rainfall and allowing some to evaporate. The spatial effects are not usually considered.

Infiltration and runoff generation

Rainfall or irrigation arriving at the soil surface is either absorbed by the soil, ponds at the surface or flows over it. The rate of infiltration of water into the soil is determined by the supply rate as long as it is less than the soil's infiltration capacity and the soil is not saturated. Once the supply rate exceeds the infiltration capacity, the process is controlled by the soil and runoff may occur. Runoff caused by the rainfall rate exceeding the infiltration capacity of the surface soil is referred to as *infiltration-excess runoff* or *Hortonian runoff* (after Horton 1933).

Runoff may also occur where there is a drainage impediment at depth and the upper parts or entirety of the soil profile becomes saturated through rainfall infiltration leading to the generation of runoff. Runoff caused by saturation of the soil profile – preventing further infiltration – is termed *saturation-excess runoff*. Saturation-excess runoff is often coupled with, and partly controlled by, lateral subsurface flow processes.

Runoff generated by either of these mechanisms can either infiltrate further downslope or enter streams. Thus, infiltration rate directly affects stream flow, water available to vegetation and erosion risk.

Estimation of infiltration and mechanisms controlling runoff are often overlooked in surveys or treated qualitatively. This needs to change by increasing direct measurement (e.g. McKenzie et al. 2002) and describing the land surface more effectively. The methods of Ludwig et al. (1997) may be incorporated into the field program.

Factors affecting infiltration and runoff

The soil infiltration capacity depends on several factors.

- *Time from the start of rainfall (or irrigation).* The infiltration rate tends to decrease monotonically to eventually reach a steady-state infiltration rate characteristic of the particular soil and conditions. The decrease is primarily as a result of decreases in the matric potential gradient as water is redistributed in the soil.
- *Initial water content.* The wetter the soil, the smaller the initial infiltration rate and the less time required before steady-state infiltration capacity is exceeded.
- *Soil surface condition.* The condition of the soil surface can have an overriding effect on infiltration. A well-structured and porous soil surface has a fast hydraulic conductivity that enhances the initial infiltration rate compared with surfaces that have been compacted, or have a crust or seal, even though the impedance may only be a few millimetres thick.
- *Water repellence.* This causes a reduction in infiltration and an increase in its variation. Unlike fully wetting soil, the infiltration rate of non-wetting soil increases with time as preferred water pathways or fingers expand and the volume of repellent soil decreases.
- *Soil structural stability.* Surface conditions of soils with low structural stability change with the amount of rainfall energy to which they have been subjected. Aggregates break down as a result of raindrop impact, rapid wetting or dispersion, causing a crust to develop. This is particularly the case with cultivated soils. Their infiltration capacity is large immediately after tillage, but may quickly decrease after a few rain events as the tilth settles or crusts or both. Vegetative cover protects the surface from some of these effects

and slows the rate at which hydraulic conductivity decreases. The organic matter status affects aggregate breakdown, and sodicity affects the likelihood of dispersion.

- *Hydraulic conductivity of the surface layer.* The greater the soil hydraulic conductivity of the surface horizon, the greater the infiltration rate tends to be.
- *Surface storage.* When the rate of water supply exceeds the infiltration rate, the excess accumulates in surface depressions. Runoff begins only when the surface storage is exceeded and the depressions overflow. Surface storage capacity is the volume per unit area in which water can pond before running off. Increases of only a few millimetres depth of water detained can reduce runoff (Cresswell et al. 1992). Storage is related to surface roughness as a result of soil clods, vegetation and plant residues. Kamphorst et al. (2000) established relationships between roughness and storage capacity. Storage capacity, like surface condition, is dynamic and tends to decrease as it is subjected to more rainfall energy. The rate of decrease depends on the structural stability.

There are several soil factors affecting saturation excess runoff.

- *Hydraulic conductivity of subsurface layers.* Subsurface layers with slow hydraulic conductivity can impede the movement of wetting fronts causing the surface layers to saturate and prevent further infiltration.
- *Lateral transmissivity of the soil profile.* Where saturated conditions occur within the soil profile, there is potential for lateral flow (discussed later). The soil's capacity to transmit water laterally depends on the transmissivity, which is the product of the saturated hydraulic conductivity and soil depth, and on the topographic slope, with steeper slopes being able to transmit water more rapidly. Lateral flow reduces the likelihood of surface runoff in areas where there is a net removal of water (typically the upper and mid slopes) and increases the likelihood of surface runoff where there is a net accumulation of water (lower slopes and riparian areas).
- *Initial water content.* The initial water content also affects the likelihood of saturation occurring during an event. The critical characteristic in this case is the depth of air filled porosity available through the profile above the drainage impediment. This is known as the *saturation deficit*.

Water movement in the soil and drainage

Infiltration ceases once rain or irrigation stops and surface water storages have emptied. However, downward water movement in the soil continues – sometimes for days or weeks, albeit at a diminishing rate – as water redistributes within the soil profile. In the absence of groundwater or zones of saturation, the effect of redistribution is to wet successively deeper layers as water is drawn down from the wetted surface soil. This redistribution determines effective water storage in different soil layers for use by plants.

The rate of redistribution depends on the hydraulic properties of the conducting soil, on the initial depth of wetting and on the relative dryness of the lower soil layers. When the initial wetting depth is small and the underlying soil layers dry, redistribution is rapid, driven by both gravity and matric potential gradients. Conversely, when the soil profile is initially wet, matric potential gradients are small and redistribution is driven largely by gravity. Redistribution slows over time because (a) matric potential gradients between initially wet and dry soil decrease as the water moves out of the wet soil and into the dry, and (b) as the initially wetted zone dries, its hydraulic conductivity decreases accordingly.

Drainage occurs when water moves down beyond the root zone. Drainage is most rapid when the soil is at or near saturation; it continues at a diminishing rate so long as the potential gradient is downward.

Drainage is important because water is mostly no longer available for evapotranspiration and it can potentially recharge groundwater. Drainage can also carry agrochemicals and salts mobilised from deep in the soil profile, both of which can contaminate groundwater and, eventually, streams. Prevention of drainage relies on maintaining sufficient spare water storage capacity in the root zone to buffer against rain events, which in part depends on achieving sufficiently deep root growth. During periods of high evaporative demand, plants are constantly using water and only a small buffer is required. However, in the winter or during fallow periods, a more substantial buffer is required because it has to contain the rainfall over a longer period.

Estimation of site and profile drainage in survey has relied heavily on profile morphology, especially colour and mottling. Estimation can be improved through direct measurement of soil hydraulic properties, digital terrain analysis and interpretation of soil chemistry (e.g. salt profiles, patterns of base saturation and pH) and redoximorphic features (see *Soil colour and related redoximorphic features*).

Hydraulic conductivity of soil layers

Redistribution is controlled by the soil's hydraulic conductivity. Hydraulic conductivity commonly decreases gradually with depth as bulk density increases. In some cases, however, a soil profile has more sudden transitions in hydraulic conductivity. These can be natural, as in the case of a texture-contrast soil in which a loamy A horizon is relatively permeable and overlies a clay B horizon with very slow permeability. Such conductivity 'throttles' can be exacerbated where the upper B horizon is sodic and clay dispersion causes further blocking of pores. In other cases, restrictions can be created by compaction or smearing as a result of heavy traffic or tillage when the soil is too wet. Pans developed from accumulations of mobile compounds (e.g. silica, carbonate, iron, organic matter) can also have low permeability.

Layers with slow hydraulic conductivity can dominate water redistribution within a soil profile by controlling the rate of movement to depth. The rate at which water moves through a restrictive layer is proportional to its conductivity and inversely proportional to its thickness. During rain, such layers can cause saturation-excess runoff as described in previous paragraphs. In drier climates, restrictive layers can reduce effective water storage within the profile, because deeper layers can be wet only by sustained rainy periods. In wetter climates, they can create perched watertables, where the soil above them is regularly waterlogged even in the absence of groundwater.

Estimation of hydraulic conductivity is challenging because of its typically large spatial variation and the high cost of direct measurement. Nevertheless, aim to obtain as many direct measurements as possible and consider pedotransfer functions (McKenzie and Jacquier 1997; Griffiths et al. 1999; see *Chapter 22*).

Macropores and bypass flow

Macropores are too large to exert a capillary effect on water and only fill under saturated conditions. Some are created by biological activity – roots or soil fauna – and tend to be cylindrical in shape. Others are structural spaces between peds and aggregates (Ringrose-Voase 1991). They are created either by the shrink–swell behaviour of clay soils to produce fissures, by the packing of aggregates and particles to create irregularly shaped pores or by tillage.

Macropores are usually only a small proportion of the total pore space. However, they have a disproportionate effect on water flow in saturated conditions, causing a large increase in hydraulic conductivity between near-saturation and saturation – sometimes by three orders of magnitude (Clothier and Smettem 1990). Watson and Luxmoore (1986) observed macropore flow accounting for 73% of water infiltration in a forested reserve in the USA with 96% of the water flux running through only 0.32% of the soil volume.

Where macropores connect to the surface, a portion of the water moves rapidly through them to the subsoil, thereby ‘bypassing’ the topsoil. In such situations, the soil appears to ‘wet up from below’ rather than exhibiting a wetting front progressing downwards from the surface (e.g. Bouma and Anderson 1973; Bouma et al. 1978; Thomas and Phillips 1979). Bypass flow can have considerable impact on the water balance when water is stored deep in the profile so that less is lost by evaporation from the surface, making more available for plant use. In other situations, bypass flow can cause water – from rain or irrigation – to be lost more easily by drainage below the root zone.

Characterisation of macropores in survey is still qualitative and imprecise particularly when few soil pits are dug. Macropores are often difficult to detect (especially in deeper horizons) but can have an overriding control on local hydrology – therefore, always consider their possible role when interpreting results from surveys.

Soil water storage and availability to plants

When a soil is wet to saturation, drainage is rapid for the first few days as the largest pores drain. This water is available to plants for only a short time. After this, drainage slows considerably as progressively smaller pores empty. The state of the soil ‘after rapid drainage has effectively ceased and the soil water content has become reasonably stable’ is described as the *drained upper limit* (DUL) or *field capacity*. It is usually determined by fully wetting a soil profile that is free from plants, covering it to reduce evaporation, leaving it to drain for 2 or 3 days, and then measuring the water content. In the laboratory, the water content of an undisturbed soil specimen in a core that has been wetted and then drained to a designated matric potential is often used as a measure of the upper limit of storage in a soil horizon. The matric potential usually (arbitrarily) assumed in Australia is -10 kPa (-33 kPa is also used in the USA).

Plants are able to extract water from the soil down to potentials of about -1500 kPa, at which point they wilt permanently. Thus, the water content at -1500 kPa is termed the *permanent wilting point* and defines the *lower limit* (LL) of plant available water.

The difference between the *drained upper limit* (DUL) and the LL is taken as the *available water capacity* (AWC) (Equation 7.1).

$$AWC\% = DUL(\%, v/v) - LL(\%, v/v) \quad \text{Eqn 7.1}$$

The AWC can be summed for all layers to a chosen depth. The *total available water* in a soil profile, W , depends on soil depth, z , as follows (Equation 7.2):

$$W (mm) = \sum_{i=1}^n \frac{AWC_i(\%)}{100} \times z_i (mm) \quad \text{Eqn 7.2}$$

where n is the number of soil layers.

A deep soil clearly holds more water than a shallow one. In deep soils, the above calculation can be made over the rooting depth of a given vegetation type. Thus, W is greater for deep-rooted species than for shallower rooted ones.

The AWC is influenced by texture and structure. In general, AWC increases as soil texture gets finer until a maximum is reached around a silt loam texture; thereafter AWC decreases slightly with the clays. Well-structured soils tend to have greater AWC as a result of greater volumes of pores in the available water size range. Williams (1983) reported a range of laboratory-derived AWC in Australian soils from 9.2% for a poorly structured silty clay to 26.5% for a well-structured fine sandy loam. He reported that many texture classes were similar, falling into a range of 12% to 16%.

Soil profile layering can effectively increase water storage. If deep enough in the profile, soil layers that restrict drainage can serve to increase plant available water by maintaining wetter

conditions in the overlying soil. However, if such layers are too shallow, they can prevent wetting of the subsoil. Non-porous coarse fragments in soil reduce the volume of soil that can store water for use by plants. Refer to McKenzie et al. (2002) and Dalglish and Foale (1998) for methods of measuring AWC and see *Chapter 22* for pedotransfer functions.

Evaporation

Water returns directly to the atmosphere from land in two ways – evaporation from the soil surface and transpiration by plants. Globally, about 60% of precipitation falling on the continents is evapotranspired (Dingman 1994). For Australia the proportion is even greater at over 90%. Thus, evapotranspiration is an important component of many agricultural, hydrological and climate models. Direct measurement of evapotranspiration is more difficult and expensive than for precipitation or stream flow. An array of methods has been developed to provide estimates based on more readily measurable quantities.

Potential evapotranspiration (PET) is the rate at which evapotranspiration would occur from a large area uniformly covered with growing vegetation with access to an unlimited supply of water. The PET is used as an index of the ‘drying power’ of the climate or of the ambient meteorological conditions. Many methods have been proposed to determine PET, including temperature-based methods such as Thornthwaite (1948), radiation-based approaches such as Priestly and Taylor (1972), combination methods such as Penman-Monteith (Monteith 1965) and methods based on measuring pan (free-water) evaporation (Brutsaert 1982). The different PET estimation methods are suitable for different applications.

Synthetic, daily Class A pan evaporation data for Australia for 1910 to the present are available through the SILO Patched Point Dataset and Data Drill (see *Precipitation*). Average monthly point and areal PET rates are available from the Bureau of Meteorology and monthly values are often sufficient for hydrological modelling.

Except after heavy rain or irrigation, actual evapotranspiration is rarely equal to potential. After the soil surface has been thoroughly wet, evaporation is initially controlled by evaporative demand. Once all ponded water has evaporated and the immediate surface has dried, evaporation from the surface becomes limited by the rate at which water can move to the surface. As the surface soil dries, its matric potential drops, creating an upwards potential gradient. At the same time $K(\psi)$ falls, restricting the rate at which water can be supplied despite the upwards gradient.

Plants are able to source water for transpiration from throughout the root zone and transpiration is often the most important mechanism returning water to the atmosphere. However, as the matric potential decreases, they start reducing the rate of transpiration. The relationship between proportion of PET actually transpired and matric potential varies between different species. As the soil dries, many Australian native species start slowing transpiration earlier than species from wetter climates, to reduce the likelihood of reaching permanent wilting point (Dunin et al. 1999).

Rainfall-limited versus storage-limited conditions

In many Australian environments, water availability is a major factor limiting plant growth. It is important to distinguish between situations which are limited by a lack of rain and those limited by small plant available water capacity. Characteristics of the former situation are limited plant growth over the whole landscape, and the accumulation of salts within the soil profile as in much of inland Australia. In the latter, water is limited by the ability of the soil to store sufficient water between rainfall events. This may be due to an inherently small water holding capacity in soils of light texture, or reduced infiltration due to crusting, or restrictive layers preventing adequate movement of water into the subsoil. The result is a landscape with

more runoff or drainage, which might exhibit wet patches in low areas and features associated with runoff such as erosion gullies. Because the limitation is soil related, it is also possible that its occurrence within a landscape is more patchy.

Lateral flow processes

Pedologists often relate soil features along toposequences to hillslope hydrology, either to explain the observed morphology or to predict the performance of systems for land management. Before making such inferences, make sure you understand the basics of hillslope hydrology and lateral flow processes in particular.

Overland flow

Once runoff is initiated, the rate of overland flow is influenced by the roughness of the soil surface and the slope. Runoff will be initiated earlier and have higher velocities on steeper slopes. Flow rates will be reduced where there is, for example, a large hydraulic roughness as a result of vegetation, soil surface roughness or organic debris. Overland flow equations often have a form similar to that resulting from application of the Manning equation for the velocity of flow in open channels (e.g. Hudson 1981) (Equation 7.3):

$$v = \frac{1}{n} r^{2/3} \sqrt{s} \quad \text{Eqn 7.3}$$

where v is mean runoff flow velocity [LT^{-1}], r is hydraulic radius [L], s is slope gradient [LL^{-1}] and n is Manning's roughness coefficient. On relatively smooth surfaces, the cross-section of overland flow is very wide and shallow, so the hydraulic radius can be assumed equivalent to the depth (Emmett 1978). Values for Manning's n can be found from texts such as Hudson (1981) (the coefficient becomes larger for rougher surfaces).

Subsurface lateral flow

Subsurface lateral flow generally occurs on moderate and steep slopes where vertical drainage is impeded by a restrictive soil layer or by bedrock. If the layers above the restriction have sufficient lateral conductivity (i.e. parallel to the surface), water can flow downhill across the top of the restrictive layer. Subsurface lateral flow is generally only significant where saturated conditions exist (e.g. Anderson and Burt 1978; Hurley and Pantelis 1985), because unsaturated hydraulic conductivity rates are usually small. Germann (1989) suggests that subsurface lateral flow may be mainly the result of macropores, which only operate in saturated conditions.

The amount of lateral flow depends on several factors apart from the hydraulic conductivity of the layer through which it occurs. Because flow is not vertical, the effect of gravity is proportional to $\sin \alpha$, where α is the slope angle (or to $s/\sqrt{(10\,000 - s^2)}$ where s is the slope in percentage). The flux is also proportional to the depth of the saturated layer, since this determines the height of the cross-section through which the water will flow. Also important is the difference between the hydraulic conductivity of the transmissive layer and that of the impeding layer below. If the contrast is not sufficiently high, the vertical drainage through the impeding layer will still tend to dominate because the effect of gravity on vertical flow is not mitigated by $\sin \alpha$.

In the Australian context where evapotranspiration rates are high, the contribution of lateral flow to the local water balance is generally only significant where all the above factors are in favour of lateral flow: moderate to steep slopes, high contrast in conductivities between layers, a deep transmissive layer in which saturation can occur and substantial rainfall compared with potential evapotranspiration. In other situations, evapotranspiration or drainage tends to cause saturated conditions to be too transient.

Although lateral fluxes may only account for a small proportion of the water balance at the local scale, the volume of subsurface water arriving at a stream can still be sufficient to generate baseflow. Note that 1 mm of water discharging from 1 km² of hill slope produces 1000 m³. Sub-surface flow velocities are normally so slow that subsurface flow alone cannot deliver a significant amount of storm precipitation directly to stream flow except under special circumstances where the hydraulic conductivity of the soil is very high and slopes are steep (Pearce et al. 1986).

Lateral flows at the hillslope or catchment scale

Water that drains or runs off from one location affects the water balance at other downslope locations. Flow accumulates in two situations:

1. the slope lessens – for example below the break of slope – causing the flow velocity to decrease
2. the landscape is horizontally concave – such as at the head of a valley.

In both situations the rate of water delivery from upslope exceeds the downslope discharge capacity leading to increased depth of saturation in subsurface layers or surface water or both. If a saturated layer intersects the surface, then seepage is observed. The accumulation of water can lead to erosion and gully formation if the slope is steep and flow velocity remains high. The addition of lateral flows, both surface and subsurface, to the water balance in these flow accumulation areas increases the amount of soil water stored. This can aid plant growth, but if the additions are excessive waterlogging can occur.

Spatial variation of surface or near-surface processes

The variation of soil properties over a landscape also means that they contribute differently to the hydrological cycle. Conversely, the hydrology of a catchment affects soil development as a result of spatial variations in wetness. Hence, survey of land attributes can aid understanding and modelling of catchment hydrology, whereas an understanding of catchment hydrology can aid understanding the spatial distribution of soils.

Patterns of infiltration

Spatial variation in soil surface properties – such as particle size distribution, structural stability, porosity and hydraulic conductivity – influences the contribution different parts of the landscape make to infiltration-excess runoff within a catchment. These variations can arise from differences in parent material, weathering history, and erosional or depositional history. Factors of this sort have a long-term influence, and survey can assist in predicting the spatial distribution of infiltration properties dependent on them. In many cases, however, infiltration properties are strongly influenced by land management, especially tillage, crop residue management and grazing pressure, which change rapidly over time and sometimes space. In these situations, survey can offer information on which locations are likely to be most affected by poor management.

Variable antecedent water content

Antecedent water content has a major influence on runoff generation in situations dominated by either infiltration-excess or saturation-excess runoff. For a particular climate, the rate at which the surface soil dries between rainfall events is controlled by several factors.

- *Vegetation.* The type of vegetation and its leaf area index control water extraction from the soil and the layers from which it is extracted. When soil is fallow, drying from subsurface layers will be slow.

- *Residue cover.* Direct evaporation from the soil surface is reduced by residue cover, in particular where the soil is fallow.
- *Aspect.* Evaporative demand from northerly slopes (in the southern hemisphere) is greater.
- *Subsoil drainage.* Impeded drainage within a soil profile will tend to slow drying.
- *Topographic position.* Landscape positions where lateral flows converge (see *Lateral flows at the hillslope or catchment scale*) tend to be the wettest. Apart from receiving more water during a rain event, they also continue receiving lateral flows for some time after the event has finished.

These factors exert only a temporary influence on antecedent water content; given long enough gaps between rain events, all zones will eventually dry out. Thus, the wetter part of a catchment that causes early runoff to be generated (the source area) gradually reduces in size between events. There is often a strong seasonality to these dynamics as a result of changes in rainfall and potential evapotranspiration (Western et al. 2002).

As for other attributes affecting infiltration, the spatial distribution of some of the factors affecting antecedent moisture can be predicted using survey information, but others are influenced by current management and are predicted less easily.

Saturation source areas

The variable source area concept (Dunne and Black 1970, Dunne 1978) refers to the widely fluctuating extent within a catchment of areas that are saturated from below and actually contributing flow to the stream. The variable source area reflects overall catchment wetness, and expands during wetter periods and contracts thereafter. The extent of source areas for saturation overland flow can be estimated as a function of hillslope gradient, planform geometry (diverging, planar or converging), hydraulic conductivity, depth and flow rate (Beven and Kirkby 1979; O'Loughlin 1981).

Groundwater flow

Groundwater is water under positive (i.e. greater than atmospheric) pressure in the saturated zone of the regolith. The watertable is the fluctuating upper boundary of the groundwater, where pressure equals that of the atmosphere. Most water enters the groundwater as recharge following infiltration and vertical drainage. Rivers, streams, lakes and dams also contribute groundwater recharge. Groundwater may eventually discharge into streams, rivers, lakes or the ocean. Water also leaves the groundwater system by moving upward from the watertable into the capillary fringe, from which it may evaporate if it is sufficiently close to the surface.

Groundwater is generally slow moving (typically < 1 m/day) with residence times varying from a few years to thousands of years or more depending on the nature of the system. Groundwater is important because it is a crucial link in the hydrological cycle and the source of much of the water in our rivers. It is also a direct source of water for domestic use, irrigation and industry, and is critical to the management of contemporary environmental issues in Australia such as salinity. Water that enters streams quickly in response to rainfall events (called event flow or storm flow) is differentiated from base flow, which is water that enters from persistent sources and maintains stream flow between event flows. Base flow is often supplied by groundwater. An unconfined aquifer has a water surface at atmospheric pressure (the *watertable*) and is analogous to free-surface water flow in streams. The elevation of the watertable is determined simply as that of the water surface in an open well. Recharge usually occurs from water draining vertically to the watertable over a significant portion of the upper surface. Where both land surface elevation and recharge vary spatially, the watertable can change in depth and even intersect the soil surface.

An aquifer is confined if it is saturated throughout and bounded above and below by materials with significantly smaller hydraulic conductivity (confining layers). The water level in an observation well that penetrates a combined aquifer will rise above the upper boundary of the aquifer to coincide with the potentiometric surface. Major recharge to confined aquifers typically occurs from water infiltrating at the 'upstream' end of confined aquifers where flow is not confined and a watertable is present. Flow in confined aquifers is analogous to flow in pipes. Hydraulic conductivity, K , is an important determinant of flow in groundwater systems. When dealing with flows in which the saturated thickness, b , is only slightly variable and the flow paths are approximately horizontal, groundwater hydrologists often use the concept of aquifer transmissivity, T [L^2T^{-1}]² (Equation 7.4):

$$T \equiv bK.^1 \quad (\text{Eqn 7.4})$$

Groundwater flows are usually calculated by combining Darcy's law with expressions of the law of conservation of fluid mass (continuity) in two or three dimensions (e.g. the Laplace equation; see Dingman 1994). Climate, landform, soils and vegetation determine the temporal and areal distribution of inputs to the groundwater system, whereas directions and rates of groundwater movement are controlled by geology. Important geological influences are: (a) lithology – the mineral composition, grain size distribution and grain shape of unconsolidated materials and rocks that control the distribution of hydraulic conductivity; (b) stratigraphy – the geometric and age relations among (often) layered unconsolidated sedimentary or rock formations; and (c) structure – the disposition and arrangement of rock formations, especially as modified by folding, faulting and intrusion of igneous rocks. In alluvial aquifers, the characteristic organisation of sediments along buried paleo stream channels and other features is often important.

Unconfined aquifers have the most direct connections with other parts of the land phase of the hydrological cycle and their exploitation as water sources usually has the most direct impacts on regional hydrology. The impacts of groundwater pumping depend on aquifer properties, especially hydraulic conductivity. When conductivity is slow, the area over which groundwater pumping affects the water potential field is small with large drawdown near the well. In contrast, shallow drawdown spread over greater distances is characteristic when conductivity is fast. Excessive discharge from groundwater pumping usually causes watertables to fall, sometimes risking saltwater intrusion and reductions in stream flow. Where groundwater recharge exceeds discharge, watertables are likely to rise until a new equilibrium is approached. This process is complicit in the development of dryland salinity in parts of Australia. For example, the clearance of large areas of woodland and forest in the south-west of Western Australia from the 1880s reduced evapotranspiration with an accompanying rise in watertables. This mobilised salt in the regolith causing increases in stream water salinity and salinisation of low-lying soils. Watertables that had been below the ground surface along the valley bottoms prior to clearing rose nearly to the surface. Seepages developed at break-of-slope and the streams began to receive a larger contribution of saline groundwater seepage relative to the surface runoff than they did previously (see Peck and Hurlle 1973; Peck et al. 1981).

Stream flow

Stream flow is the sum of event flow – such as that occurring as a result of runoff during a rain-storm – and base flow from the groundwater system. The stream flow is an integral response

¹ Unfortunately, the same symbol, T , is well established in both dimensional analysis and groundwater hydrology for denoting time and transmissivity respectively.

(over space and time) dictated by: (a) the spatially and temporally varying water inputs (usually rainfall); and (b) the time required for the water to travel from where it strikes the ground to the stream and then to the point of measurement and (c) any losses to evapotranspiration along the way. A graph of stream discharge versus time is called a stream flow hydrograph. The hydrograph is the net result of the following:

- water moving within the catchment along an indefinite number of surface and subsurface flow paths (surface flow paths are generally faster than subsurface flow paths)
- each flow path accumulating inputs of water
- during an event and while the land surface is draining, the stream network is an accumulation of lateral inflows from the flow paths distributed along the channel length
- during a storm event, flow in the stream takes the form of a flood wave that moves downstream through the stream network (the observed hydrograph records the movement of the flood wave past the fixed point of measurement)
- some time after the beginning of an event, the flow rate usually increases relatively quickly from the pre-event rate to a peak discharge and then declines more slowly (the hydrograph recession) back towards its pre-event rate.

The magnitude of a flow event is essentially determined by rainfall and the degree to which catchment surface water storage capacity is already filled (i.e. how wet the catchment is prior to the event). The types of water storage capacity that function in a rain event are: (a) water intercepted on the vegetative canopy which is filled then evaporates quickly and usually constitutes only a small proportion of a stream flow producing event; (b) depression storage which reflects slope and surface roughness; and most importantly (c) the soil water storage capacity, the largest component. Available soil water storage capacity (ΔS) at the time when water input begins ($t = 0$) is given by (Equation 7.5):

$$\Delta S_{(t=0)} = [\phi - \theta_{(t=0)}]z_{(t=0)} \quad (\text{Eqn 7.5})$$

where ϕ is soil porosity, θ is soil water content, and z is depth to the watertable (all averaged over the catchment).

The flow mechanisms that produce responses to stream flow events can be summarised as:

- precipitation falling directly into the channel (usually a small contribution)
- surface runoff (infiltration or saturation-excess mechanisms)
- subsurface flow
- saturated flow from local groundwater mounds
- flow from perched saturated zones (matrix or macropore flow)
- unsaturated flow.

Understanding hydrological response requires knowledge of both hillslope processes and flow-in channel networks. There are various methods of predicting stream flow including those detailed in Dingman (1994).

Relative importance of individual processes in contrasting climates

Hortonian flow is more prevalent in semi-arid to arid areas where rainfall intensity is high and surface cover is often sparse, leaving the soil surface vulnerable to crusting as a result of raindrop impact. Saturation runoff is more commonly associated with humid regions – watertables are often coincident with the stream surface and hence not far below the ground surface near the stream. Rainfall events cause recharge and increase watertable height. Close to the stream, the watertable reaches the surface, and subsequent water input travels as overland flow across this zone to the stream.

Hydrological significance of soil features

Soil colour and related redoximorphic features

Hydrology is both affected by soil properties and affects them. Certain morphological features provide indicators of local hydrology, especially where the soil is frequently wet causing reducing conditions. Such features are referred to as redoximorphic. However, some caution is needed with their interpretation in case they are a relict of a previous hydrological regime.

Mottles

Mottles form where soil is waterlogged for long periods leading to reduction of iron from its Fe^{3+} (ferric) form to its Fe^{2+} (ferrous) form. Minerals formed from Fe^{3+} tend to be dominated by red or brown colours, whereas those formed from Fe^{2+} tend to be yellow or grey. Hence, the more time that a soil spends saturated, the more it will develop yellow or grey colours. However, the degree of reduction and its duration can vary over small distances (centimetres), causing mottling patterns. Furthermore, Fe^{3+} is generally immobile, and Fe^{2+} mobile. Iron in zones with prolonged saturation becomes mobile; some of this Fe^{2+} diffuses into more oxidised zones where it transforms to Fe^{3+} and is immobilised. This results in a net migration away from reduced zones. The pattern of redoximorphic features can reveal more than that the soil is subject to prolonged waterlogging. Where there is groundwater within the soil profile, the soil will generally be grey due to reduction of iron – referred to as gleying. Near the watertable depth there is usually characteristic mottling because the soil is subject to alternating reducing and oxidising conditions as the watertable fluctuates. When the watertable falls, the first zones to dry out are those bordering macropores, which develop orange mottling. Thus, grey ped interiors and mottled exteriors are indicative of persistent groundwater (e.g. Vepraskas 1992).

In other situations, soil layers with reduced hydraulic conductivity may create a perched watertable. Here the pattern of mottling is different because water tends to persist in the macropores leading into the restrictive layer. The zones near macropores tend to be more reduced and greyer than the soil matrix.

Pay close attention to the colours and patterns of mottling during survey. Refer to overseas manuals more recent than the current Australian field handbook (McDonald et al. 1990) for specific guidelines on redoximorphic features (e.g. Schoeneberger et al. 2002).

Bleached horizons

Bleached A2 horizons are a common feature of Australian soils. Bleaching results from the removal of iron and destruction of clay minerals. Such bleaching is often indicative of soil subject to transient saturation because of the slow conductivity of the underlying soil (Fritsch and Fitzpatrick 1994). Water is held up above the restrictive layer long enough for iron to be reduced and mobilised, but as it moves slowly either downwards into the B horizon or laterally downslope, it carries away the iron.

Hydrological modelling

Classification of models

Beck (1991) and Wheeler et al. (1993) developed a classification framework for hydrological models identifying metric, conceptual and physically based models. This framework is used here following Hatton et al. (1998) to structure the discussion while acknowledging that many models have characteristics of more than one type as part of a continuum of different approaches.

Metric models

Metric models use non-linear mathematical expressions to transform input data such as rainfall to output data such as stream flow. The equations are strictly empirical, are not related to preconceived process descriptions, and are selected for their generality. Metric models have minimal data requirements, are easy to apply and can be used across a range of scales. Their limitations include difficulties in application in ungauged catchments, and lack of capacity to predict effects of land use, land management or climate change. The basic assumptions of this type of approach tend to include homogeneity in infiltration capacity, evaporation, rainfall distribution and rainfall intensity. The method has been applied to large areas through disaggregation of the region into more uniform subunits. Rodriguez-Iturbe and Valdes (1979) and van der Tak and Bras (1989) advanced the notion of geomorphological unit hydrographs to scale models to the basin level. The development of metric models has included the splitting into 'quick' and 'slow' (storm flow and base flow) responses (Wheater et al. 1993); treatment of separate flow systems and reservoirs; and efficient inversion techniques for estimating model parameters. Jakeman et al. (1990) provide a review of the long history of this type of hydrological modelling. Well-known Australian examples of conceptual models include IHACRES (Identification of unit Hydrographs and Component flows from Rainfalls, Evaporation and Stream flow data) (Jakeman et al. 1990; Jakeman and Hornberger 1993).

Conceptual models

A catchment can be conceptualised as a series of interconnecting water stores with fluxes between them. This structure, together with the laws of conservation of mass, can provide the basis for formulating conceptual catchment models. These models contain a set of mathematical equations describing the movement of water into, between and out of various stores considered important in a catchment. There are hundreds of such models varying in complexity according to the number of stores incorporated and the equations used. These conceptual models are distinguished from metric models in that the model structure and the mathematical form of connecting the equations are specified *a priori*. Parameters are determined through subjective methods or objective criteria, and often limits are placed on the ranges of specific parameter values.

The advantages of conceptual models are that they help to formalise ideas about the structure of catchments and their water and solute balances. In theory, some if not all of their parameters may be subject to independent measurement. The potential impacts of land use change may be predicted if the model was formulated for that purpose.

The disadvantages of conceptual models lie in their large numbers of parameters. In this regard, model complexity (i.e. the potential parameter space) often exceeds the information content of the available data (Beven 1989, Wheater et al. 1993). Thus, it becomes difficult to calibrate such models against observed data. In addition, the parameters estimated for such models are almost always scale-dependent, and because they are often lumped, cannot be measured. Parameters are usually calibrated.

Well-known Australian examples of conceptual models include SoilWat (Keating et al. 2003), LASCAM (Large Scale CATCHment Model) (Sivapalan et al. 1996a,b,c) and IQQM (Integrated water Quantity and Quality Model) (New South Wales Department of Land and Water Conservation 1998).

Physically based models

Physically based models are similar to conceptual models in that the relevant processes are represented. The difference is that water and solute movement are described by the fundamental physical equations based on conservation of mass and energy that are assumed to represent

the catchment system. Increased computational capacity has allowed fast solution of the relevant flow equations. Water and nutrient fluxes and storages occurring in different parts of a catchment can be modelled explicitly using a variety of different space and time scales. There is a variety of water balance, catchment hydrology and groundwater models that are physically based. Well-known Australian examples include SWIM (Ross 1990; Verburg et al. 1996) and TOPOG (O'Loughlin 1986; Hatton et al. 1992; Vertessy et al. 1993).

The advantages of distributed parameter, physically based catchment process models lie in their ability to incorporate the *known* spatial heterogeneity of soils, geology, rainfall and vegetation (management) into predictions of catchment behaviour that are themselves explicit in space. Like their non-spatial counterparts, conceptual models, they emphasise generality over precision and can thus be applied to ungauged catchments, although this almost always requires a period of subjective optimisation (calibration). They can potentially accommodate both diffuse and point source pollution (solute) phenomena and relate the fluxes of these compounds to specific changes in the management of specific portions of the catchment.

Such physically based models have all of the drawbacks regarding parameterisation as discussed for conceptual models, but with even more extreme imbalances between the data required to run them, the number of parameters and the uncertainty of deriving a unique solution. The philosophical debate on this subject is an old and active one (e.g. Beven 1989, 1993) concerning issues of heterogeneity and scale, and the spatial and temporal inferencing of the soil, hydrogeologic and climate parameters required by these models.

Physically based models (and those intermediate between conceptual and physically based) are widely used because of the ongoing need to predict the impact of specific changes in land use or land management in ungauged catchments. Judicious use of such models is usefully informing catchment management, as are applications of metric and conceptual models.

Soil information for hydrological modelling

Soil hydraulic properties

Fundamental to the use of either conceptual or physically based models is obtaining values for model parameters. In both cases, many of these are the soil hydraulic properties that, as discussed earlier, are important determinants of hydrological processes. The key properties that are often required for each soil horizon as inputs for physically based models are:

- saturated hydraulic conductivity
- hydraulic conductivity as a function of water content or water potential (termed unsaturated hydraulic conductivity)
- the soil water characteristic (the relation between soil water content and matric potential). Implicit is water content at saturation which relates closely to total porosity with a correction for air entrapment.

Conceptual models usually require an estimate of the active soil moisture storage capacity of a catchment.

Unsaturated hydraulic conductivity and the soil water characteristic are often described by fitting non-linear models (analytical functions) (e.g. Campbell 1974; van Genuchten 1980) to the measured data points. These functions provide a basis for interpolation between points, are often used directly in numerical models, and are important for prediction of these properties (e.g. Cresswell and Paydar 1996; Williams et al. 1992). For example, closed-form methods for prediction of unsaturated hydraulic conductivity utilise the fitting of models to water characteristic data along with a measured saturated (or near saturated) hydraulic conductivity

measurement (e.g. Campbell 1974; van Genuchten 1980). Some hydrological models simply use the variables of well-known forms of hydraulic functions as the model input.

Each of the above hydraulic properties is measurable at a point but more difficult to ascribe across an area because of soil spatial variation. However, there is enormous potential for land resource surveys to provide soil hydraulic properties for whole landscapes so that they can be modelled, and provision of such data should be seen as one of the major purposes for survey.

Methods for measuring hydraulic properties are described by McKenzie et al. (2002), as are the advantages and disadvantages of each method in particular situations. The major difficulty is that most hydraulic properties are time-consuming and therefore expensive to measure, especially in the context of a survey. Laboratory-based measurements require volumetric or intact (undisturbed) specimens which are time-consuming to collect. Measurement, whether in the field or laboratory, is also expensive.

Considerable scientific effort has gone into the development of methods to predict soil hydraulic properties and to combine field survey with hydraulic property prediction. Pedotransfer functions, which are methods to predict soil hydraulic properties from more easily measured soil attributes, are very helpful in hydraulic property characterisation (see *Chapter 22*). Widespread application and further development of pedotransfer functions requires a database of hydraulic property measurements using comparable methods. For soil survey to reach its full potential as a provider of spatial data for hydrological models, a more systematic collection of hydraulic property data during survey programs is necessary. Cresswell et al. (1999) described a survey process for soil hydraulic properties that incorporated reference sites with direct hydraulic measurement, combined with the use of functional horizons, functional morphologic descriptors and pedotransfer functions to extrapolate to other parts of the landscape. Their approach remains valid and needs to be implemented with some urgency in Australia.

Conceptual models, such as tipping-bucket (or storage overflow) water balances, require a transfer coefficient that controls the rate of downward water movement between soil layers. The coefficient is not one that can be directly measured. It is sometimes empirically related to saturated hydraulic conductivity but is commonly determined through model calibration.

Parameters for infiltration and runoff

The primary step in most water balance models is the partitioning of rainfall into runoff and infiltration. This partitioning is sensitive to surface conditions or the profile saturation status or both. It is subject to considerable spatial and temporal variability. This makes it very difficult to predict at a landscape scale. This can lead to a lack of confidence in distributed parameter models, because the sum of predictions made over a whole catchment are difficult to match to catchment measurements of runoff obtained by stream gauging.

The USDA Soil Conservation Service (1972) curve number approach is one of the most robust approaches in a survey context. The procedure uses total precipitation on a given day to estimate runoff. Runoff curve numbers (CN, i.e. runoff as a function of total daily rainfall) are specified by numbers from 0 (no runoff) to 100 (all runoff). Curve numbers are obtained from measurements from runoff plots, which are clearly not practicable in a survey. Littleboy (1997) developed a simple estimate of curve number based on a score of the condition of the soil surface and the slope. This approach is associated with conceptual models such as SoilWat and predicts infiltration-excess runoff.

Physically based models, such as SWIM, can model infiltration accurately at the point scale but require many parameters to do so, including:

- surface hydraulic conductivity and its rate of decline during a rainfall event
- surface depressional storage (depth) and its rate of decline during a rainfall event

- saturated hydraulic conductivity, unsaturated hydraulic conductivity and the soil water characteristic (see *Soil water characteristic*).

Although the properties relating to surface soil condition can be obtained at a plot scale for research purposes, they are highly variable in time and cannot be practically obtained in a survey context.

Estimates of storage

Both conceptual and physically based models require estimates of the capacity of the soil to store water. Physically based models require knowledge of water content at saturation and the soil water characteristic, as discussed above. Conceptual models, for example those which use a tipping-bucket (or storage overflow) water balance approach, require an estimate of the storage capacity parameters for each store in the model. These can be estimated from the following for each soil horizon:

- water content at saturation
- drained upper limit (field capacity)
- lower limit (wilting point).

Water content at saturation, θ_s , can be determined by measuring the water content of the field saturated profile. More commonly, it is determined by calculating total porosity from a measurement of bulk density and then correcting the porosity to allow for air entrapment. Typically, 5% or 7% air entrapment is assumed (i.e. $\theta_s = 0.93 \times \text{total porosity}$, or $\theta_s = 0.95 \times \text{total porosity}$). As discussed (see *Soil water storage and availability to plants*), the drained upper limit and the lower limit can be obtained from the soil water characteristic or by measuring the water content in the same profile on several different occasions to capture it in a fully wet up and completely dried state (see Dalglish and Foale 1998). If necessary, the profile can be wetted artificially. Measurements can be made using a neutron moisture meter or by gravimetric sampling.

Soil water storage is also a function of rooting depth, which varies greatly between species and can be impeded by soil layers that are inhospitable because they are hard, water-logged, acid, saline, deficient in nutrients or toxic. Rooting depth is not included currently in a routine land resource survey but the use of a hydraulic push-tube soil corer and the 'core-break' method is an attractive approach. Once a core is collected and removed from the coring tube, the core is simply broken to expose horizontal faces and these are checked for the presence or absence of roots. Checking at progressively greater depth enables an estimate of rooting depth. Alternatively, but less practical in a survey context, monitoring soil water content as a function of depth can be undertaken to estimate maximum depth of water plant extraction.

Groundwater

Many groundwater models are based on Darcy's law for saturated flow which can be written as (Equation 7.6):

$$V_x \equiv \frac{Q}{A_x} = -K_{hx} \frac{dh}{dx} \quad \text{Eqn 7.6}$$

where V_x is the specific discharge [LT^{-1}], which is defined as the volume rate of flow Q [L^3T^{-1}] per unit area A_x [L^2] of porous medium at right angles to the x direction. The K_{hx} [LT^{-1}] is the saturated hydraulic conductivity of the medium in the x direction, and h [L] is the total hydraulic head of the fluid. Thus, the models require specification of the hydraulic conductivity, the cross-sectional area of flow, porosity, the hydraulic gradients and boundary conditions. Boundary conditions might, for example, be a zero vertical flux boundary at the bottom surface of an aquifer, or a constant head outlet boundary condition where the groundwater intersects the soil or stream channel. Often

aquifer properties such as section width, surface area, base elevation, and groundwater levels can be set at each of a series of cross sections along the direction of flow. Multiple branches of aquifers can also be merged into a single flow tube. It follows that aquifer properties such as hydraulic conductivity are required for each aquifer section that is differentiated. This type of model construct is exemplified, for example, with the FLOWTUBE model (Dawes et al. 2000), designed as a relatively simple groundwater calculator for examining the long-term average effects of different recharge and discharge options on catchment groundwater.

Core logs are important to specify the physical dimensions of the aquifers, along with geological and topographical mapping (to help estimate aquifer width). Groundwater levels or measurement of piezometric heads are required for specification of initial hydraulic gradients. Many groundwater models also require temporal estimates of recharge, sometimes provided through simple rainfall-recharge relationships such as those of Zhang et al. (2001). In practice, and in the absence of measured data, hydraulic conductivity is often estimated from tabulated values such as those given by Freeze and Cherry (1980). Groundwater predictions are usually sensitive to the hydraulic conductivity inputs, however, and thus can require calibration, a tricky process given the uncertainties in recharge estimation and discharge capacity.

While soil survey data are not likely to directly inform groundwater modelling and interpretation to any great extent, it is highly relevant to the estimation of recharge which is a key driver for groundwater analysis.

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Vegetation

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Introduction

This chapter provides guidelines and methods for the capture, interpretation and management of vegetation data and information which, if followed, will meet the requirements of the National Vegetation Information System (NVIS) (NLWRA 2001, ESCAVI 2003). Its aim is to assist vegetation scientists to survey, classify and map vegetation types to the association and subassociation level of detail (ESCAVI 2003). Description and mapping of vegetation is presented as a four-phase process:

1. survey design and planning
2. recording of vegetation attributes in the field
3. data analysis to determine and map vegetation types
4. generation of final outputs.

It is best to closely link the four phases, but in practice they are often poorly integrated. The chapter concludes by describing the current status of vegetation data and information held in the NVIS data set. Future developments are outlined and emphasis is placed on the need for a framework to monitor vegetation extent, change and condition.

Applications and providers of information

Decision-makers involved in many issues of public and private land management require consistent and reliable information on the type and extent of vegetation. Such information is important for the effective development and implementation of policies and initiatives including:

- obligations to reduce greenhouse gas emissions
- conservation of biodiversity
- control of land degradation
- protection of endangered species
- sustainable management of forests
- fire management
- pest and weed control
- agricultural production.

Australia also has both international and national obligations for monitoring and reporting which, directly or indirectly, call for reliable and comprehensive vegetation data.

Key agencies for vegetation survey and mapping in the states and territories of Australia are generally the departments for natural resource management. At the Commonwealth level, the

Department of Agriculture, Fisheries and Forestry and the Department of the Environment and Heritage are involved in coordinating vegetation information and reporting.

Vegetation mapping was essential in formulating Regional Forest Agreements in New South Wales, Victoria, Tasmania and Western Australia. In recent years vegetation clearing laws have been introduced in most states; to administer them vegetation classification and mapping are essential. For example, regional ecosystem maps in Queensland are certified legal documents and the current extent of vegetation based on these maps determines conservation status (Wilson et al. 2002). Right across Australia, vegetation maps are increasingly used as primary inputs for regional planning.

Types of vegetation information include lists of plant species, maps of both species distributions and vegetation types. To provide sound guidance, a wide range of ancillary data needs to be combined with the basic vegetation information. For example, to estimate the distribution of pre-1750 species and vegetation communities (Austin et al. 2000), maps of elevation and soil types are vital. As discussed in the chapter, to understand the use and condition of vegetation, other relevant social, economic and environmental information need to be considered.

National Vegetation Information System – NVIS

Since the late 1940s, vegetation scientists have developed and used a wide variety of survey, classification and mapping systems for Australian vegetation (Benson 1995, Sun et al. 1997). As a result, it can be difficult to compare or combine data sets. Whereas some classification and mapping systems have been developed to translate and compile existing mapped data sets (e.g. AUSLIG 1990, ESCAVI 2003), generally only sets with sufficient features in common (e.g. attribute detail, scale of mapping, theme of mapping) can be compared or combined.

A diverse range of vegetation survey, classification and mapping systems continue to be used across Australia, even though uniformity and consistency in survey and mapping systems have been desirable goals set by most researchers, ecologists and land managers (Gillison and Anderson 1981, Myers et al. 1984, Gunn et al. 1988, Margules and Austin 1991). In the late 1990s, agencies with an interest in vegetation mapping collaborated to develop the National Vegetation Information System (NVIS) (NLWRA 2001). NVIS relies on the widely used vegetation classification system developed by Walker and Hopkins (1990).

NVIS was developed and populated with existing maps of present-day and pre-European (pre-clearing or pre-1750) vegetation maps (Thackway et al. 2001). The NVIS 2000 data set includes variables for growth form, structure (height and cover), and floristic composition of native vegetation (NLWRA 2001, Thackway et al. 2001). All of Australia's environments were covered, including grasslands, rangelands, shrublands, mangroves, open woodlands and forests. Vegetation descriptions did include some exotics (pastures and weeds).

NVIS uses a consistent set of structural and floristic attributes. As a consequence, much of the information in the *Australian Vegetation Attribute Manual* (ESCAVI 2003) is relevant to specifications for new vegetation survey, classification and mapping. The NVIS framework is discussed further below.

Principles and terms

Vegetation refers to the patterns of plant species that occur in repeating assemblages across the landscape. Before attempting to survey, classify and map vegetation, some basic concepts need to be explained. Austin (1985) noted that most plant ecologists consider the community concept underlying most vegetation mapping to be a convenience rather than a reality. Debates about concepts of species distributions and the reality and utility of the plant community have strong parallels with debates on patterns of soil attributes and the reality and utility of soil

types. Most species are individualistic in their distribution across the landscape, but some are distributed regularly in both environmental and geographical space. Vegetation types rarely occur as single-species stands but rather as assemblages of species that form a continuum in terms of abundance, cover and height and these respond to environmental gradients. The fundamental unit of vegetation description and mapping in Australia is the *plant association* – a vegetation community of defined floristic composition and structural form (ESCAVI 2003).

The terms *survey*, *classification* and *mapping* are used in various ways by vegetation scientists. In this chapter the terms are used in the following way.

Surveying is looking comprehensively for an entity or entities usually in a defined region. Vegetation surveys aim to discover and document the occurrence of one or more plant species. They vary from surveys of rare and threatened plants or specific taxonomic groups (in which selected plants are targeted) through to comprehensive surveys (where the aim is to document all species).

Classification involves the creation of classes or categories. This usually involves combining the various mixtures of plant species and structural attributes recorded at sites into groups or classes that others can recognise. Classification may be made on structural, floristic or environmental grounds, or a combination of these, and may be based on all the attributes present or only a selection (e.g. only trees or dominant species).

Mapping is the process of depicting the spatial extent of a classified entity. Maps may show individual species or classified communities. Comprehensive mapping usually requires modelling of some form. Remotely sensed imagery or numerical models are used with site data to provide predictions of vegetation distribution across the whole landscape (i.e. environmental correlation – see *Chapters 2 and 22*).

The processes used in vegetation survey, mapping and classification in Australia are summarised in Figure 8.1.

Classification

Vegetation communities may vary continuously both in time and space. Beadle and Costin (1952, p. 61) state that:

any attempt to classify a continuously varying system into several categories must necessarily be somewhat arbitrary, in so far as at some points the system must be broken into distinct groups. The selection of these critical points constitutes a controversial issue, since classification is essentially a compromise between the desire to preserve these natural groupings as continuously varying entities and the need to subdivide them for more utilitarian purposes.

Beadle and Costin (1952) capture the essence of the problem facing vegetation surveyors, or for that matter, most types of natural resource survey. Breaking continua of independently distributed species into discrete entities such as plant communities – as proposed in the Gleason model and supported by the niche model (Austin 1985) – requires subjective human judgement on where in geographical space the most appropriate boundary or threshold occurs. This task is made easier when similar environmental conditions produce clumping of species into recognisable and predictable plant assemblages.

Most vegetation mappers in Australia proceed largely intuitively (Kirkpatrick and Dickinson 1986) using qualitative techniques for data analysis (Figure 8.1). However, numerical techniques are being used increasingly (e.g. Wilson et al. 1990, Keith and Saunders 1990, Keith and Bedward 1999, Austin et al. 2000).

In the qualitative approach, site data – floristic, structural or both – are classified into vegetation types. Maps are derived by establishing relationships between the interpreted spatial patterns of the vegetation – observed, say, in remotely sensed images – and the classified site data.

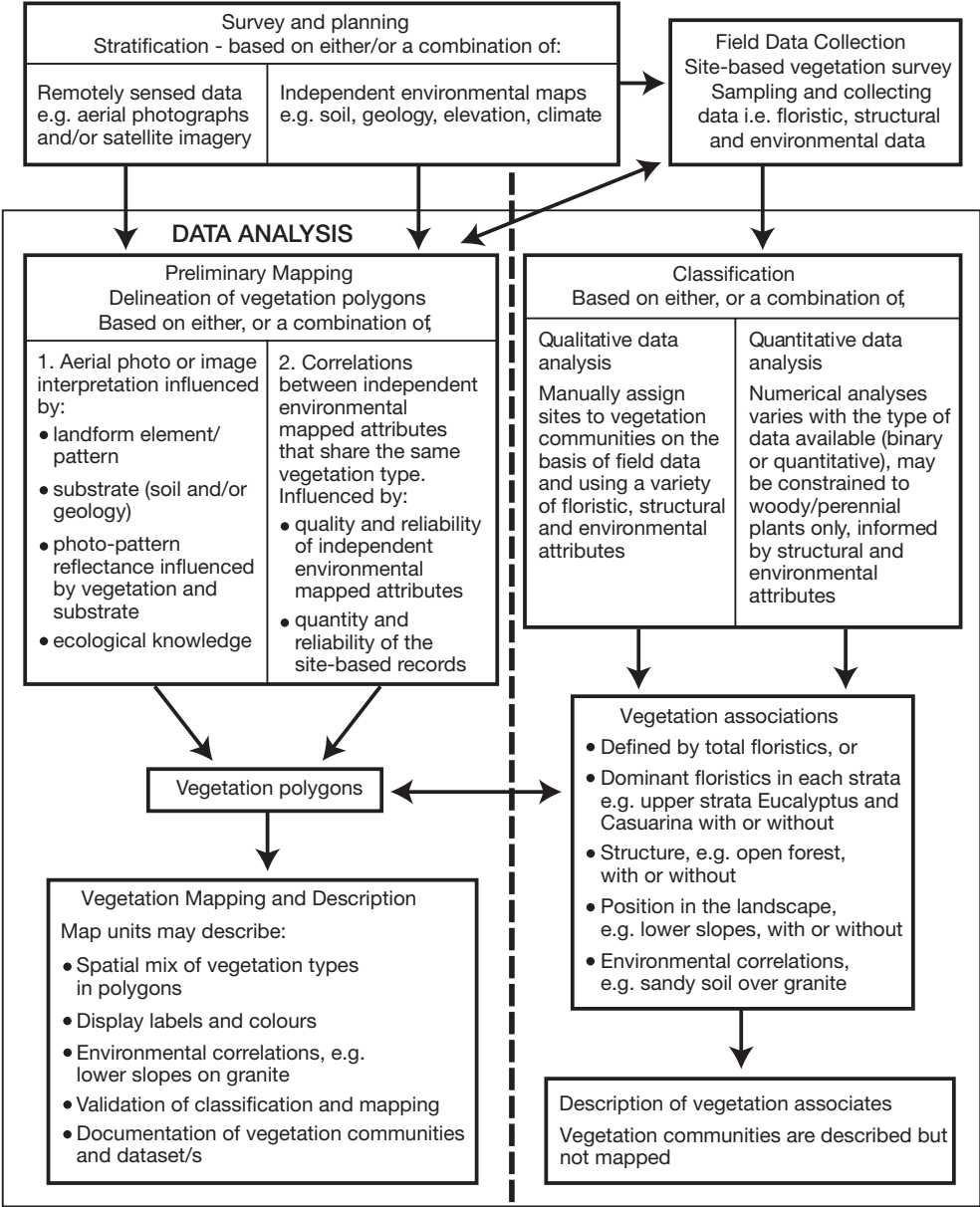


Figure 8.1 The processes used in vegetation mapping and classification in Australia (after Neldner et al. 2004b).

In the quantitative approach, site data (again floristic, structural or both) are classified into vegetation types. Maps of vegetation are derived from explicit relationships between the environmental attributes for the region and the classified site data.

The final output of many vegetation studies is a classification of vegetation with descriptions of vegetation assemblages. Vegetation assemblages can be based on an intuitive classification or numerical analysis, with varying degrees of expert knowledge incorporated into the

final groupings. Many vegetation assemblages defined by numerical techniques are difficult to map. They are often amalgamated with more extensive or spatially coherent units (Kirkpatrick and Dickinson 1986). Coutts and Dale (1989) and Neldner and Howitt (1991) compared manual and computer-based vegetation classifications with the vegetation communities defined, respectively, for a 1:5000 and 1:25 000 scale vegetation map. They found broad agreement in the groupings. However, correspondence at finer detail was limited because environmental variables were not incorporated into the numerical analysis. The right-hand pathway in Figure 8.1 represents studies where the distribution of the classified vegetation communities is not spatially represented in a map.

Mapping vegetation communities

Vegetation maps are produced through spatial extension of site data. Two broad approaches are used and these are represented on the similarly numbered boxes in the left-hand pathway of Figure 8.1.

1. Visual interpretation of patterns on air photos (see *Chapter 10*) or numerical analysis of the spectral reflectance of satellite imagery (see *Chapters 11 and 12*) covering the entire region.
2. Modelling vegetation distribution across a region using numerical relationships between site-based vegetation data and independent environmental variables. These relationships are used to predict the environmental domains of individual species or assemblages. Once the numerical models are developed and related to environmental attributes in a geographical information system (GIS), the predicted distribution can be shown as maps. Modelling of species or assemblages may extend to the whole landscape or be constrained (e.g. to the present extent of native vegetation cover).

The objective of air-photo interpretation is recognition, delineation, definition and description of vegetation patterns. As shown in Figure 8.1, the delineation of vegetation boundaries uses several other factors including landform, information on substrate (geology, soils), and, importantly, the site data and field knowledge of the interpreter. Sivertsen and Smith (2003) provide useful guidelines for delineating photo-patterns for native vegetation based on tones or textures.

Vegetation mapping is an interactive process of establishing a relationship between the spatial units (either delineated on remotely sensed imagery or defined through statistical modelling) and the vegetation units (floristic groups, association or subassociations, or both) they contain. The process of developing a map requires the mapper to link each land unit tract to the vegetation units (Figure 8.1). The vegetation maps produced by the two approaches are similar but have important distinctions. Map units of the former relate to the visible spatial patterns interpreted from remote sensing imagery (e.g. rainforest can be delineated as generally dark photo-patterns); in the latter, map units are a function of correlations between environmental attributes (e.g. sites with rainforest are typically found on particular soil and geology types, and restricted to particular elevation, slope, aspect, climate). The final maps may be either polygon-based (e.g. NVIS 2000) or grid-based (e.g. major vegetation groups NLWRA 2001).

The most effective method for gaining an ecological understanding of species distributions is through substantial periods of field work. In some studies (e.g. Forestry Tasmania's Forest Typing), air-photo interpretation is done by laboratory-based experts. In most other vegetation surveys, the field ecologist either does the air-photo interpretation, or at least has a major role in the process (Harris and Kitchener 2005). Knowledge of the distribution of species in the landscape is imperative for mapping the distribution of vegetation communities, particularly closely

related units (e.g. open forests dominated by *Eucalyptus* species where the reflectance of the different species is very similar). In these situations, substrate and position in landscape often determine species composition, and these are used to delineate communities. Most satellite images do not allow stereoscopic viewing (except SPOT) and, because of the importance of topography in interpretation, their use is limited to mapping vegetation communities across large areas. The grain of much imagery is relatively coarse (e.g. ~30 m with data from the LANDSAT Thematic Mapper) when compared to air photographs, and this limits discrimination of vegetation patterns. LANDSAT TM data have been used successfully for broad-scale mapping (e.g. Wilson et al. 1990), structural typing of vegetation (e.g. Ritman 1995) and land-cover change detection (AGO 2002).

Survey design and planning

This section provides an overview of the design and planning of vegetation surveys. There are many parallels with land resource surveys. Before each step is considered, the relationship between vegetation and integrated surveys needs to be clarified (see also *Chapter 12*).

Relationship between vegetation and integrated surveys

In the 1940s through to the 1980s, integrated surveys (see *Chapter 2*) were made over large areas of Australia by CSIRO and state and territory agencies. These surveys mapped *land systems*, which were made up of repeated patterns of component land units (Christian and Stewart 1953). Although these integrated surveys covered the whole landscape, they were biased towards land systems with perceived agricultural potential. Integrated surveys involve multidisciplinary teams to enable the collection of comprehensive information on vegetation, soils and geology. This approach can lead synergistically to a greater understanding of the environmental variables and ecological processes determining the distribution of vegetation types. The land system mapping for these projects was generally done by pedologists or geomorphologists; vegetation, soils and agricultural potential maps were then derived from the land systems map through the use of generic relationships.

Although there are many advantages with this efficient approach, compromises are made, especially with sampling. For example, vegetation maps for Central Western Queensland were derived primarily from the land system mapping, but additional vegetation communities were delineated, particularly in the alluvial and residual land systems, and extra sampling in these areas was required (Neldner 1991).

In recent times, the expertise in the various land resource disciplines has been dispersed across agencies, and integrated surveys are now relatively uncommon. Integrated biodiversity surveys, where vegetation and fauna experts work together, are sometimes made. These surveys require flexible fieldwork because the time needed for sampling fauna is different from sampling vegetation. An alternative to integrated field teams is to mark sites permanently, allowing teams from each discipline to sample the same sites at the optimal time. The use of Global Positioning Systems (GPS) has made the task of relocating sites easier and more accurate.

Coordination

Sound project planning is needed for surveys of vegetation (see *Chapters 14* and *15*). This applies equally to one-off vegetation maps and to state-wide mapping programs. Clearly specified outputs, highly skilled staff, adequate resources (for both office-based and field-based activities) and careful planning are essential. Mapping programs require clear standards, effective coordination and good communication. Staff training and calibration are also necessary.

Define the purpose

Clearly define the purpose of each vegetation survey at the beginning. In particular, define the target population and its geographical extent: will the survey include vegetation across the whole landscape or will it be restricted to selected land tenures, such as production forests, national parks or native vegetation only? Be clear on the type of mapping required (e.g. comprehensive floristic inventory or vegetation at the community level).

Many vegetation surveys focus essentially on native vegetation, ignoring non-native vegetation and non-vegetated areas. However, even in such cases, native vegetation needs to be defined and this can be difficult. For example, in New South Wales, undisturbed vegetation and regrowth older than 10 years is defined as native vegetation (Sivertsen and Smith 2003). In Queensland, only remnant native vegetation, as defined by specific structural and floristic attributes, is mapped for the purposes of the *Vegetation Management Act 1999* (Neldner et al. 2005).

More detailed mapping may further classify native vegetation into various condition classes, based on canopy height, cover, weediness and old growth (Woodgate et al. 1994). Depending on the purpose of the study, information on the extant native vegetation (present at the time of survey or date of imagery used) or pre-clearing vegetation (pre-1750 or pre-European) may be required. In the latter case, modelling and historical data can be used to produce pre-clearing maps (Neldner et al. 2005). Extant vegetation can be derived from the intersection of a map showing the pre-clearing distribution and a map of remnant vegetation derived from recent satellite imagery (e.g. Neldner et al. 2005).

If all vegetation in fragmented landscapes needs to be mapped, then land cover types that define native, non-native and non-vegetated areas can be used. For example, areas can be mapped as native vegetation, potential native vegetation (herbaceous with a previous cultivation pattern) and non-native or non-vegetated. Where a polygon is noted as non-native or non-vegetated, no further description may be required. Land units designated as native vegetation or potential native vegetation (forest, woodland, native pasture) should be fully described (Sivertsen and Smith 2003). Where there is a need to further discriminate non-native vegetation, it will be necessary to develop a series of vegetation and land cover classes (see *Chapter 9*).

Once a decision is made on the target population, select a description and classification system. In native vegetation, it is common to use schemes based on a combination of structural and floristic characteristics of the vegetation (e.g. Specht 1970, Beard and Webb 1974, Walker and Hopkins 1990). Other schemes include regional ecosystems (Sattler and Williams 1999, Wilson et al. 2002) and ecological vegetation classes (Woodgate et al. 1994) – these include landscape and environmental attributes in the classification.

Scale

Most of the issues of scale (see *Chapter 3*) apply to vegetation surveys. In most studies, the resolution of mapping is set by the imagery used for mapping (satellite or air-photo). While normal cartographic standards relating to scale should be applied to maps, GISs allow users to rescale maps with ease. This emphasises the need for metadata that clearly define the limits to their use. The extent of the study region, purpose of survey, available resources (expertise, time, funds), seasonality and access all influence map resolution and quality. Table 8.1 presents size limits of features set by cartographic constraints.

Within each land unit, define the pattern of discrete floristic groups, subassociations or associations. These may be homogeneous (pure) or mixed (mosaics). Spatially mixed land units have several discrete floristic groups, associations or subassociations. As a general rule, land units should be homogeneous within the tolerances of the final mapping scale. This makes for simpler interpretation and analysis. However, heterogeneous land units can depict

Table 8.1 Size limits of mapped features set by cartographic constraints (after Bureau of Rural Sciences 2002)

	Size on map	Cartographic scale			
		1:25 000	1:50 000	1:100 000	1:250 000
Area of the smallest mapped feature	2 × 2 mm	0.25 ha	1.0 ha	4 ha	25 ha
Minimum width for linear features	1 mm	25 m	50 m	100 m	250 m

several vegetation units detectable on the imagery but unable to be mapped separately at the scale of the study. With more detailed mapping, these components could be mapped out separately. Record the proportion of a land unit occupied by each vegetation unit to enable accurate estimates of total areas.

Survey design

The principles of survey design, and sampling in particular (see *Chapter 20*), are similar for vegetation and soil survey. However, it is often more important in vegetation studies to adequately sample the full range of biotic and environmental variation. Effective stratification is essential. Figure 8.1 presents stratification in the context of the processes used in vegetation mapping and classification. Preferably, the set of independent attributes of the physical environment that are used should explain the distribution of the plant species (Austin et al. 2000). Several methods of data analysis and display can be used to assess the adequacy of sampling in geographical and environmental space (e.g. Neldner et al. 1995, Ferrier and Watson 1997, Tropical Savannas Cooperative Research Center 2001). Myers et al. (1984), Gunn et al. (1988), Pedley (1988) and Margules and Austin (1991) provide useful guidance.

Stratified sampling of some form provides a logical and efficient method for plot-based sampling. Strategies include use of ecological gradients, random and representative sampling, stratified random sampling, and gradient-oriented transect (gradsect) sampling. The preferred approach in Queensland and New South Wales agencies is representative sampling within environmental sampling units (Neldner 1993, Sivertsen and Smith 2003). More sample plots are allocated to more extensive vegetation units. Randomising within units removes bias. In areas where access is limited, randomised or grid-based sampling is frequently more expensive, and more sophisticated designs are then required.

Always be aware of potential bias as a result of land use, tenure or both. Another source of bias is associated with the nature of the vegetation. If native vegetation is the target and the purpose is to describe typical or modal vegetation, then sample plots should be allocated in areas that show least disturbance. The concept of a *type-site* or benchmark site has been widely recommended. However, it is important to sample several typical sites across the extent of the vegetation to capture a wide range of variation. As a general rule, the more sites that are recorded within a study area, the better will be the final product (Sivertsen and Smith 2003). The guideline in New South Wales is that where complex patterns are observed in environmental sampling units, in excess of 200 sampling plots will be required for a 1:100 000 map sheet. However, for the same area in which the environmental sampling units exhibit broad patterns, 100–200 sample plots are adequate (Sivertsen and Smith 2003).

If the aim of the survey is to describe the full range of vegetation, then sample ecotones and disturbed vegetation in addition to undisturbed vegetation. Take care to understand the impact of land management on vegetation structure and composition: in some instances, the impact of agriculture on composition of the ground layer is difficult to assess.

Sampling plots

Comprehensive data are priceless and enduring and will be used many times over. Although informal observations are often made during fieldwork, it is preferable to use formal sample sites wherever possible.

Consider the purpose, size and shape of the sampling plot. A range of strategies may be appropriate. For example, the vegetation mapping program in Queensland has four types of sampling plot ranging from primary sites (for repeat sampling) to quaternary sites (points used only to confirm mapping) (Neldner et al. 2005).

There is an inevitable trade-off between plot size and number of plots. Species–area curves are useful in determining the most efficient plot size for certain vegetation types (capture most of the species on site – alpha diversity); they can also be used to assess and the number of plots needed to capture the full range of species occurring across the extent of the vegetation type (beta diversity) (Mueller-Dombois and Ellenberg 1974, Kent and Coker 1992). In northern Australia, aside from rainforests, a 500-m² plot captures most of the alpha diversity on a site (Neldner 1993). At least 10 plots are required to effectively sample the beta diversity of heathland and savanna vegetation on Cape York Peninsula (Neldner et al. 1995, Neldner 1996). Sivertsen and Smith (2003) note that plot area is more important than shape. Oblong plots are generally more efficient than other shapes (Greig-Smith 1964, Neldner 1993) and they should be oriented along the contour (Austin 1978, Walker and Hopkins 1990, Neldner 1993).

The time taken to complete recording at a site depends on many factors: the structural, floristic and environmental attributes to be recorded; the skill of the botanist or ecologist; the vegetation type and condition; the seasonal conditions; terrain; and the methods used. It is therefore impossible to accurately judge the time necessary to complete recording. Nevertheless, it will generally be at least 20–30 minutes (Noy-Meir 1970, Austin 1978) and up to 3 or 4 hours in complex rainforest.

Databases and checking data

Vegetation survey is laborious and collecting new data expensive. Surveyors should aim to collect data once and encourage its use many times. Systems have to be established and maintained for collecting, entering, storing and analysing vegetation data. Relational database management systems are essential, and these must link to land unit and environmental data held in GISs.

During planning, be clear to distinguish between attributes that describe the characteristics of each site (typically visualised as point data in a GIS) and attributes describing vegetation associations and subassociations (typically describing land unit tracts).

Enter data as soon as possible after field survey. Apply automated checking processes (e.g. completeness of data, GPS locations in correct map sheet, plant names match plant census) (see *Chapter 16*).

Collection of vegetation attributes in the field

Stratification of layers

Users find vegetation information easier to understand when vegetation types are described with simple structural and floristic descriptors. Although no classification will satisfy all purposes, consensus on describing and mapping native vegetation favours a system based on:

- structural formation (i.e. growth form such as tree or grass)
- height
- cover (percent cover of each growth form).

These items of information are provided for each stratum (layers of vegetation) and are complemented by floristic assemblages (i.e. dominant or diagnostic species found in one or more strata).

Structural formation can be derived from several classifications (e.g. Specht 1970, Specht 1981, Walker and Hopkins 1990). Collect primary data (e.g. growth form, height, cover, floristics) rather than predetermined classes (Sun et al. 1997). This allows sites to be easily allocated to any structural classification. Structural formations provide strict definitions as well as an easily understandable summary of the dominant growth form, cover and height of a vegetation description. For example, in the terminology of NVIS, vegetation is classed as *open shrubland* when it comprises shrubs <2 m in height with 10% to 30% foliage cover.

Botanists need to recognise the layering in vegetation (strata) in a similar manner. Figure 8.2 illustrates the layers recognised at both the association and subassociation level. Figure 8.2 also shows two examples of vegetation profiles. A definitive vegetation type for a region can be described at the subassociation level (NVIS Level VI) by interpreting the variation within each substratum across the relevant sites. For example, median values of height and cover from the relevant sites could be used to describe the vegetation type. However, depending on the purpose of the mapping, the interpreter may choose to discard, or place less emphasis on, data from some sites to produce a tractable number of vegetation types (and classes in the final legend on the map). When a similar process is used comprehensively across all vegetation in the region, the resulting types could be labelled ‘definitive’.



Figure 8.2 Vegetation profiles for two different vegetation types, showing the flexibility in assignment of substrata. These become key inputs for NVIS descriptions at the subassociation level. At the association level, only the strata U (Upper), M (Mid) and G (Ground) are recognised (i.e. dominant species from U1 and in some cases diagnostic species from U2 are listed in the U strata).

Site-based vegetation attributes

Collect and classify a combination of structural and floristic attributes to enable effective description and mapping of vegetation communities (i.e. associations and subassociations). Not all field attributes are of equal importance: for example, floristic composition is defined as all species occurring within a plant community. The value of floristic information will often depend on the time of sampling. Sampling during the dry season will usually limit the number of annual species that have living tissues present (Neldner et al. 2004).

Structural data (e.g. strata, growth form, height and foliage cover) collected at sites can be summarised and graphically represented for each association across its distribution. Figure 8.3 shows foliage cover and height within strata for three growth forms (e.g. trees in the upper storey). These continuous variables subsequently can be grouped into height and cover classes.

In Australia, the most widely used guidelines for collecting structural and floristic vegetation data at field sites are those of Walker and Hopkins (1990). They were enhanced in the late 1990s through the development of the NVIS framework. This involved their implementation in a relational database that linked vegetation descriptions to map units (map legend information) in a GIS. Walker and Hopkin's (1990) system was expanded from a site-based field-survey method to a system for describing and mapping vegetation associations and subassociations across whole regions. The structural and floristic attributes required for the NVIS association and subassociation (Table 8.2) need to be collected and documented because they:

- provide basic reference information to enable vegetation classification and mapping at the association and subassociation level
- assist in the management and transfer of records within vegetation data sets.

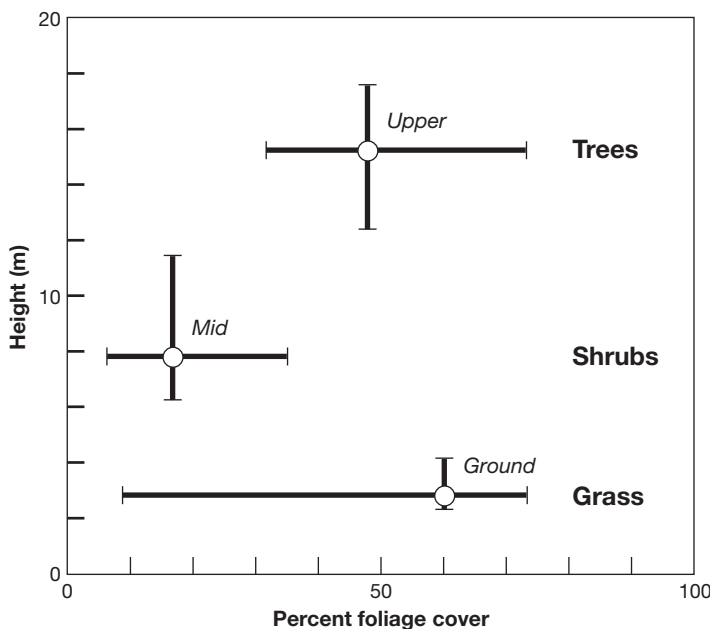


Figure 8.3 Schematic for a vegetation association showing the median, maximum and minimum values for height and cover in three strata (upper, mid and ground) dominated by three separate growth forms.

Absence of these core attributes may render the relevant records in a data set unusable for classifying vegetation at the association and subassociation level. Walker and Hopkins (1990) is being revised further at present (Hnatiuk et al. 2008).

Table 8.2 describes the attributes required to develop vegetation associations and subassociations in NVIS. The attributes listed in Table 8.2 are derived largely from Walker and Hopkins (1990). Other guidelines for site attributes include those of Bolton (1992), Davey et al. (1993),

Table 8.2 Attributes required to develop NVIS vegetation associations and subassociations

Category	Attribute	Description
Structural data	Stratum code	At NVIS Level 6, each substratum is described by a code (i.e. a letter that corresponds with the stratum, and a number that describes the position within the stratum of a particular substratum). The code is assigned in order of decreasing relative height, e.g. U1 > U2 > U3. For data collected at NVIS Level 5, the valid options are U, M and G.
	Cover type	The type of measure used (e.g. crown or canopy cover, foliage cover, percentage cover, projective foliage cover, crown or canopy cover, foliage cover, percentage cover, projective foliage cover, cover abundance rating) This attribute is usually the same for a given survey.
	Cover mean value	A percentage value expressed as the mean for the substratum (e.g. 60%)
	Height type	Describes the method used to provide the height value (e.g. layer height (general vegetation mapping), average height (general vegetation mapping), general height of the top of the tallest canopy layer, not necessarily the dominant canopy layer). Again, this attribute is usually the same for a given survey
	Height mean value	The mean height for the substratum expressed in metres
Growth form data	Dominant stratum flag	Indication as to whether the stratum (or substratum) is dominant, relative to all other strata, within the vegetation community being described
	Growth form rank	Rank of each growth form within the substratum in order of decreasing importance in describing the substratum or stratum
	Growth form code	Symbol and name for identifying growth forms in a substratum or stratum
Taxon data	Other attributes	Further ecological attributes can be collected (e.g. to describe the cover and height of each growth form)
	Taxon data rank	Each taxon (species) is ranked in order of decreasing importance within each substratum. Generally the cover value is ranked after sites are grouped (i.e. experts rank at the site as dominant, common, occasional)
	Taxon data description	Describes the full taxonomic names of the taxon (i.e. genus + species + infraspecies rank + infraspecies). (This attribute is under review. It is now recommended that taxon names be split into their component names: genus, species, etc)
	Other attributes	Further ecological attributes can be collected at each site – e.g. to describe the cover, height, leaf size and phenology of each taxon (Bolton 1992)

Similar attributes are collected at the site level. A detailed description of each attribute is presented in the Australian Vegetation Attribute Manual (ESCAVI 2003).

state and territory proformas, and database programs (e.g. CORVEG, see McDonald and Dillewaard 1994).

These site-based attributes are recorded on field sheets and include reference and locational information (Bolton 1992). Other attributes (in addition to those listed below) include those relating to environmental characteristics at the site (e.g. elevation, geology, lithology, landform, microrelief, soils, land use, degree of disturbance).

Data analysis – classification and mapping

Generating derived attributes

To construct a vegetation description, vegetation attributes need to be summarised (Table 8.3). These attributes are generated from simple summary statistics of the site database, or simple interpretations of the site data, or both.

Classification of data

Goodall (1953a, 1953b) was an Australian pioneer in the objective classification of vegetation, and his work has had a profound impact on the discipline. Since that time, numerical methods developed in Australia have been at the forefront (e.g. Lance and Williams 1967, Williams 1976, Minchin 1987, Belbin 1988, Faith 1991). The most commonly used numerical analysis programs in Australia are PATN (Belbin 1988), TWINSpan (Hill 1994) and Canoco (ter Braak and Smilauer 1998). See *Chapter 21* for discussion of methods of exploratory data analysis contained in these programs, especially those for ordination and classification.

Table 8.3 Field attributes used to construct vegetation descriptions at the association and subassociation level.

Category	Attribute	Description
Structural data	Cover code	Cover measurement for the stratum or sub-stratum. Summarises the cover measure in a form that is comparable across different methods of measurement (e.g. d = crown cover 80–100%).
	Height Class	Categorises the height for each sub-stratum. Summarises the height measure in a form which is comparable across different methods of measurement. It contributes to the definition of the structural formation of the sub-stratum.
Growth form data	Growth form summary flag	Indicates whether the particular growth form is required as a descriptor to characterise the stratum at simpler levels in the NVIS framework
Taxon data	Taxon data always there	Describes whether the species is always present throughout the extent of the vegetation type. A simple interpretation of frequency in the context of generating vegetation descriptions with +/- symbols between relevant species
	Taxon data summary flag	Describes whether a particular genus is required as a descriptor to characterise the stratum at simpler levels in the NVIS Information Hierarchy and whether the word 'mixed' should be appended to a stratum description
	Taxon data frequency	The number of sites with a particular taxon (species) (within each substratum), expressed as a percentage of all sites

Definitions of attributes are presented in the Australian Vegetation Attribute Manual (ESCAVI 2003)

Ordination methods assist in the interpretation of classifications by providing insight into the relationships between sites, as well as checking the validity of site or species groups. Classification techniques seek to recognise communities and to characterise these in terms of species composition and environmental attributes. Vegetation types (associations, subassociations) can be derived by various methods of exploratory data analysis. In essence, the methods search for pattern or structure in field data. Exploratory data analysis can be used to help set limits to vegetation units, and to explore alternative ways of organising the units. Explore your data and prepare an intuitive vegetation map because both together generate more information than either alone (Mueller-Dombois and Ellenberg 1974, Kirkpatrick and Dickinson 1986, Austin and McKenzie 1988, Austin 1991, Neldner 1993).

The type of data used in these analyses varies greatly. Most analyses rely only on presence or absence (binary) data for native perennial or woody species. Analyses can also use structural data. Environmental data are generally used to aid interpretation of the resulting groups. Quantitative data on species (e.g. stem density or basal area for each species) are less frequently used because they are scarce. Neldner and Howitt (1991) found that analyses based on basal area and stem density were a better guide for the dominance of species within each site group than those that relied on binary floristic data. Classifications derived solely from canopy species can be as informative as those based on detailed floristics at the scales shown in Table 8.1 (Webb et al. 1967, Neldner and Howitt 1991, Bedward et al. 1992).

The results of numerical classification of site data can be used to describe and delineate vegetation communities. Figure 8.1 shows where numerical classification fits into the method for vegetation survey and analysis.

To summarise, the main purpose of classification is to develop discrete and recognisable vegetation types (association, subassociation or both) in a robust and consistent way. The result may then allow each discrete vegetation type to be defined and incorporated into a useful system. The vegetation types can be used and refined as knowledge improves. Newly defined vegetation types may be included within the existing system or necessitate the creation of a new system.

Local classifications usually apply to a single study region (i.e. project or data set) but comparison and integration will be required across multiple study regions and jurisdictions. The development of definitive vegetation types (based on association or subassociation for native vegetation) provides the basic building block for describing land units in a GIS.

The definition of vegetation associations and subassociations requires structural data (i.e. stratum, height, growth forms, foliage cover). Table 8.4 describes how these attributes are classified into layers (substratum) and Table 8.5 outlines the derivation of structural formations.

Conversion from sub association to association is complex, and requires much expertise. Simpler levels than vegetation association can be derived automatically provided the data are consistent and stored in a relational database.

Mapping

The process of classification and mapping extant or present vegetation involves an iterative matching of the classification (i.e. a list of vegetation types at the level of association, subassociation or both) with the patterns of vegetation observed on aerial photos and delineated through statistical modelling.

Inevitably, there is a trade-off between the two classifications because the taxonomic and mapping units use different criteria – the same issues that arise in soil survey. Consideration also needs to be given to the publication scale of the map and the scope of vegetation types to be included. The latter may range from all native vegetation, old growth native forests and native forests managed for timber production, native and modified pastures, to clearly anthropogenic

Table 8.4 Descriptions of NVIS substratum codes and their defining structural attributes (ESCAVI 2003)

NVIS stratum code	NVIS substratum code	Description	Traditional stratum name	Growth forms*	Height classes ^A	Disallowed ^A
U	U1	Tallest tree substratum	Upper; tree; overstorey; canopy	Trees, tree mallees, palms, vines (mallee shrubs)	8, 7, 6 (5)	Grasses and shrubs, low mallee shrubs
		For forests and woodlands this will generally be the dominant stratum	(The code U1 is used if only one tree layer occurs)	Also: epiphytes, lichens		
		For a continuum (e.g. no distinct or discernible layering in the vegetation) the tallest stratum becomes the defining substratum				
	U2	Subcanopy layer, second tree layer				
	U3	Subcanopy layer, third tree layer				
M	M1	Tallest shrub layer	Mid; shrub (The code M1 is used if only one mid-layer occurs)	Shrubs, low trees, mallee shrubs, vines, (low shrubs, tall grasses, tall forbs, tall sedges) grass-trees, tree-ferns, cycads, palms	(6) 5, 4, 3	Mid- and low-grasses, sedges, rushes and forbs
	M2	Next shrub layer		Also: epiphytes, lichens		Mid and tall trees/palms
	M3	Third shrub layer				
G	G1	Tallest ground species	Lower; ground (The code G1 is used if only one ground-layer occurs)	Grasses, forbs, sedges, rushes, vines, lichens, epiphytes, low shrubs, ferns, bryophytes, cycads, grass-trees, aquatics, seagrasses	(4, 3) 2, 1	Trees, tree-mallees, palms
	G2	Ground				

Table 8.5 Structural attributes used to create NVIS Structural Formations (ESCAVI 2003)

	Cover characteristics							
	Foliage cover (%)	70–100	30–70	10–30	<10	≈ 0	0–5	Unknown
	Crown cover (%)	> 80	50–80	20–50	0.25–20	< 0.25	0–5	Unknown
	% Cover	> 80	50–80	20–50	0.25–20	< 0.25	0–5	Unknown
	Cover code	d	c	i	r	bi	bc	Unknown
Growth form	Height ranges (m)	Structural formation classes						
Tree, palm	< 10, 10–30, > 30	Closed forest	Open forest	Woodland	Open woodland	Isolated trees	Isolated clumps of trees	Trees
Tree mallee	< 3, < 10, 10–30	Closed mallee forest	Open mallee forest	Mallee woodland	Open mallee woodland	Isolated mallee trees	Isolated clumps of mallee trees	Mallee trees
Shrub, cycad, grass-tree, tree-fern	< 1, 1–2, > 2	Closed shrubland	Shrubland	Open shrubland	Sparse shrubland	Isolated shrubs	Isolated clumps of shrubs	Shrubs
Mallee shrub	< 3, < 10, 10–30	Closed mallee shrubland	Mallee shrubland	Open mallee shrubland	Sparse mallee shrubland	Isolated mallee shrubs	Isolated clumps of mallee shrubs	Mallee shrubs
Heath shrub	< 1, 1–2, > 2	Closed heathland	Heathland	Open heathland	Sparse heathland	Isolated heath shrubs	Isolated clumps of heath shrubs	Heath shrubs
Chenopod shrub	< 1, 1–2, > 2	Closed chenopod shrubland	Chenopod shrubland	Open chenopod shrubland	Sparse chenopod shrubland	Isolated chenopod shrubs	Isolated clumps of chenopod shrubs	Chenopod shrubs
Samphire shrub	< 0.5, > 0.5	Closed samphire shrubland	Samphire shrubland	Open samphire shrubland	Sparse samphire shrubland	Isolated samphire shrubs	Isolated clumps of samphire shrubs	Samphire shrubs
Hummock grass	< 2, > 2	Closed hummock grassland	Hummock grassland	Open hummock grassland	Sparse hummock grassland	Isolated hummock grasses	Isolated clumps of hummock grasses	Hummock grasses

Growth form	Height ranges (m)	Structural formation classes						
		Closed tussock grassland	Tussock grassland	Open tussock grassland	Sparse tussock grassland	Isolated tussock grasses	Isolated clumps of tussock grasses	Tussock grasses
Other grass	< 0.5, > 0.5	Closed grassland	Grassland	Open grassland	Sparse grassland	Isolated grasses	Isolated clumps of grasses	Other grasses
Sedge	< 0.5, > 0.5	Closed sedgeland	Sedgeland	Open sedgeland	Sparse sedgeland	Isolated sedges	Isolated clumps of sedges	Sedges
Rush	< 0.5, > 0.5	Closed rushland	Rushland	Open rushland	Sparse rushland	Isolated rushes	Isolated clumps of rushes	Rushes
Forb	< 0.5, > 0.5	Closed forbland	Forbland	Open forbland	Sparse forbland	Isolated forbs	Isolated clumps of forbs	Forbs
Fern	< 1, 1–2, > 2	Closed fernland	Fernland	Open fernland	Sparse fernland	Isolated ferns	Isolated clumps of ferns	Ferns
Bryophyte	< 0.5	Closed bryophyteland	Bryophyteland	Open bryophyteland	Sparse bryophyteland	Isolated bryophytes	Isolated clumps of bryophytes	Bryophytes
Lichen	< 0.5	Closed lichenland	Lichenland	Open lichenland	Sparse lichenland	Isolated lichens	Isolated clumps of lichens	Lichens
Vine	< 10, 10–30, > 30	Closed vineland	Vineland	Open vineland	Sparse vineland	Isolated vines	Isolated clumps of vines	Vines
Aquatic	0–0.5, < 1	Closed aquatic bed	Aquatic bed	Open aquatic bed	Sparse aquatics	Isolated aquatics	Isolated clumps of aquatics	Aquatics
Seagrass	0–0.5, < 1	Closed seagrassbed	Seagrassbed	Open seagrassbed	Sparse seagrassbed	Isolated seagrasses	Isolated clumps of seagrasses	Seagrasses

vegetation, such as field crops, horticulture and forest plantations. Surveyors also need to define whether vegetation dominated by aggressive naturalised exotics is to be mapped. Harris and Kitchener (2005) present an example of a technical manual used for choosing and allocating vegetation types encountered during routine mapping of air-photo patterns. This manual demonstrates the value of historic and comprehensive field survey and classification that now underpins the Tasmanian Vegetation Mapping Program.

Independent validation

Reliability codes have been incorporated in some maps to guide users on the botanist's confidence on interpretations for each land-unit tract (Neldner et al. 2005). Assessments of sampling adequacy provide an indication of field-data quality underpinning the map (Neldner et al. 1995). Peer review is an important part of quality assurance. However, the most rigorous assessment of accuracy is through independent validation. Validate the map and classification in the field shortly before its release and give users a clear measure of attribute and spatial accuracy (Sivertsen and Smith 2003).

Edge mapping and equivalence

Map-makers vary in their style and the amount of detail they accommodate. A common distinction is made between 'splitters' and 'lumpers'. Splitters try to map all the variation they observe in the field, whereas lumpers believe it is important to place closely associated vegetation types together in a single class (because the types may function similarly ecologically and there is less risk of being incorrect if the mapped unit is broad). There are many variants between these poles. Where several botanists are involved in a large program, adopt a consistent level of definition (e.g. scale and resolution). This is crucial in allowing edge-matching and production of state-wide and nation-wide vegetation coverages.

When several study regions are involved, coordinate, validate and assure quality to ensure seamless transition from one region to another. Ensure consistency in the classification and mapping procedures between teams and assess accuracy of the results against the agreed specifications. Where teams are working in adjacent regions, ensure they understand the classification and mapping to be used, and map outwards from shared boundaries.

Final outputs

The vegetation map is the primary output in most studies. Comprehensive reports are also desirable. Outline the physical characteristics of the study region (e.g. climate, soils, geology, landform); describe in detail the vegetation map units; and list plant species comprehensively. Photographs provide important visual summaries of vegetation.

Make sure you enter and validate all data, complete metadata documentation, and archive field data and GIS layers. Document methods used for quality assurance and attend to the validation procedures used to assess the accuracy of classification and mapping.

Metadata

Metadata provide a structured description and summary of each data set. They define the content, currency, access, availability and quality of the data (see *Chapter 25*). Document all vegetation data sets using the latest definitions for metadata. Remember that metadata allow a potential user to assess whether a set of data fits their purpose. NVIS collaborators have developed additional metadata elements for vegetation. These elements link to ANZLIC metadata attributes and summarise the various phases of a vegetation mapping project (Table 8.6, Figure 8.1).

Table 8.6 Attributes used to document the phases of a vegetation mapping project

Category	Attribute	Description	Phases of a vegetation mapping project
Reference information	Data set name	Plain-English name for the dataset	All phases
	Vegetation theme	Describes what the vegetation data set represents (e.g. estimated pre-1750 and/or present vegetation types and their extent)	All phases
	Start date attributes	Date of the earliest field collection of vegetation-related attributes used in the survey underpinning the maps	Field data collection
	End date attributes	Date of the latest field collection of vegetation-related attributes used in the survey underpinning the maps	Field data collection
Vegetation attribute methods and accuracy	Structural classification system	Classification system used in the field survey and mapping method (e.g. Walker and Hopkins 1990). This attribute can also be used to document whether the data were collected using class ranges rather than discretely measured values (e.g. older mapping and land system/unit mapping)	Data analysis – classification
	Classification method	The method/s used to create the vegetation types. It includes the classification and/or ordination package/s used e.g. PATN, the particular module used e.g. UPGMA, and the parameters selected and the rationale for their selection	Data analysis – classification
	Floristic group type	Describes the method by which species are selected to define each floristic group in the dataset (i.e. the choice of up to 5 species in the level 6 description). This field should identify whether the vegetation descriptions contain: (i) species that contribute the most biomass (or cover/abundance), (ii) indicator species or (iii) a mixture of both types of species	Data analysis – classification
	Sampling type	The type of site plots used to derive and/or field check the map, survey or project	Field data collection
Spatial methods, positional accuracy and useable scales			Final outputs
	Map publication scale	The scale at which the vegetation map and data set is to be published	Data analysis – mapping
			Final outputs
	Positional accuracy	The accuracy, in metres, of mapped line or cell features in relation to their real world locations (e.g. nearness to the real-world geo-referenced location) across the data set	Data analysis – mapping

(Continued)

Table 8.6 (Continued)

Category	Attribute	Description	Phases of a vegetation mapping project
	Positional accuracy determination	The positional source or determination of points, polygons or cells across the data set. The information provided should relate to the type of data (i.e. point, polygon or raster, rectified satellite image, mapped topographic features, differential global positioning system)	Data analysis – mapping
Summary of survey and mapping methods and accuracy	Survey and map reliability	A description of the overall reliability in the survey and mapping methods (spatial/positional and attributes/ecological) used to derive the data set	Final outputs
	Start date attributes	Date of the earliest field collection of vegetation-related attributes used in the survey underpinning the map of the study area	Field data collection
	End date – attributes	Date of the latest field collection of vegetation-related attributes used in the survey underpinning the map of the study area	Field data collection
	Start date – spatial	Date of the earliest image used in the mapping of the study area	Data analysis – mapping
	End date – spatial	Date of the earliest image used in the mapping of the study area	Data analysis – mapping
Map origins (methods and sources)	Mapping method	Describes the interpretive tools used for delineating the map units within the data set. e.g. aerial photo interpretation; manual satellite image interpretation; combination of quantitative modelling and aerial photo interpretation	Data analysis – mapping
	Imagery source	Describes the type of image used to derive/classify the mapping units (e.g. black and white aerial photography, colour aerial photography, satellite imagery: LANDSAT Thematic Mapper)	Data analysis – mapping
	Imagery scale	Cartographic scale of each image listed in imagery source expressed using the relative fraction (e.g. 1:25 000)	Data analysis – mapping
	Start date – source	Date of the earliest image used in the field sampling and later the mapping of a subset of the study area	Data analysis – mapping
	End date – source	Date of the most recent image used the field sampling and later the mapping of a subset of the study area	Data analysis – mapping
References	Citation	A full reference to a publication, includes reports, technical manuals, journal articles that describe the data set and/or the methods used in its compilation (e.g. AUSLIG 1990)	Final outputs

Detailed descriptions of each attribute are presented in the Australian Vegetation Attribute Manual (ESCAVI 2003)

Vegetation mapping may be updated regularly. For example, in Queensland updates to the remnant regional-ecosystem coverages are undertaken every two years. It is essential in these cases to maintain clear and unambiguous release dates and version numbers. Increasingly, map outputs are published on the Internet, allowing cheap and easy access to many users. This makes controlling versions even more important, especially when the maps are used for regulatory purposes.

How the National Vegetation Information System works

The NVIS aims to capture consistent vegetation information across the nation at a variety of scales (see *National Vegetation Information System – NVIS*). For this, the data need to be exchanged at the association and subassociation level, as defined in the NVIS Attribute Manual (ESCAVI 2003). Tables 8.4 and 8.5 describe the attributes needed to define structural components of vegetation types. These structural components, when combined with information on species dominance (Table 8.3), produce an integrated NVIS vegetation description (i.e. association, subassociation).

The *subassociation* level in NVIS has up to eight substrata or layers, with characteristic height and cover recorded for each. Up to five growth forms and five species in each layer can be used to describe the vegetation type.

The *association* level in NVIS uses the three traditional strata (i.e. upper, mid, ground) if they are present (Walker and Hopkins 1990; Figures 8.2 and 8.3). For each stratum, the characteristic height and cover (and their ranges) are recorded. Up to three growth forms and three species per stratum can be used to describe the vegetation type.

Vegetation description at association and subassociation levels might be too detailed for many uses and they can be aggregated into simpler units with the NVIS Information Hierarchy. This hierarchy uses structural information in the first instance and then the dominant genus and growth form collected at the substratum level. Moving up the hierarchy to a simpler level involves two steps:

1. definition of the dominant substratum (usually defined as contributing most to above ground-biomass)
2. definition of the dominant species and growth form (i.e. the most representative).

A completed NVIS vegetation description shows how the association and subassociation vegetation description can be simplified (Table 8.7).

The extent and scales of the vegetation data available in the NVIS 2005 present-vegetation data set is shown in relation to the Intensive Landuse Zone (ILZ) (Figure 8.4). The figure shows detailed vegetation mapping (i.e. less than 1:50 000 scale) in areas of south-east Australia. Coarse-scale mapping (i.e. less detailed than 1:1 000 000) occurs in a small area in central New South Wales and large areas of central and northern Australia, including most of the Northern Territory, large areas in South Australia, north-west New South Wales and south of the Gulf of Carpentaria in Queensland. Obvious gaps in the ILZ occur where vegetation mapping is coarser than a 1:100 000 scale. These areas include the south-west and north-west of Western Australia, areas of the northern ILZ in South Australia, a large area in western New South Wales, and the area south of the Gulf of Carpentaria in Queensland.

The extent and scale of estimated pre-European vegetation is shown in Figure 8.5. Compared with the NVIS 2005 present-vegetation dataset, large areas of Australia do not have detailed mapping available for estimated pre-European vegetation. The best quality mapping is available across all of Victoria, Tasmania, much of central and southern Queensland, and small areas of eastern New South Wales. Very coarse-scale mapping (i.e. less detailed than 1:1 000 000) is available in South Australia and most of New South Wales and a small area of

Table 8.7 The NVIS information hierarchy with examples

For definitions of U, M, G, U1, U2, U3, M1, M2, M3, G1, and G2 refer to Table 1 of the Australian Vegetation Attribute Manual (ESCAVI 2003)

Level	Description	Species	Growth form	Cover	Height
I	Class	–	One dominant growth form for the dominant stratum	–	–
	Example	<i>Tree</i>			
II	Structural formation	–	One dominant growth form for the dominant stratum	One cover class for the dominant stratum	One height class for the dominant stratum
	Example	<i>Open woodland</i>			
III	Broad floristic formation	One dominant genus name for the dominant stratum	One dominant growth form for dominant stratum	One cover class for dominant stratum	One height class for dominant stratum
	Example	<i>Eucalyptus open woodland</i>			
IV	Subformation	One dominant genus name for each stratum (maximum of 3 strata; i.e. for U, M, G where substantially present)	One dominant growth form for each stratum (maximum of 3 strata)	One cover class for each stratum (maximum of 3 strata)	One height class for each stratum (maximum of 3 strata)
	Example	<i>+Eucalyptus open woodland\Acacia tall sparse shrubland\Aristida open tussock grassland</i>			
V	Association	Up to 3 dominant species for each stratum (maximum of 3 strata; i.e. for U, M, G where present)	Up to 3 dominant growth forms for each stratum (maximum of 3 strata; i.e. for U, M, G where present)	One cover class code for each stratum (maximum of 3 strata; i.e. for U, M, G where present)	One height class code for each stratum (maximum of 3 strata; i.e. for U, M, G where present)
	Example	<i>U+ ^Eucalyptus coolabah, Casuarina cristata, Flindersia maculosa/^tree/7/r;M ^Acacia salicina, Alectryon oleifolius, Acacia stenophylla/^shrub/4/r;G ^Aristida ramosa, Astrebla squarrosa, Bothriochloa decipiens/^tussock grass,forb,sedge/2/i</i>			
VI	Subassociation	Up to 5 dominant species for each substratum (i.e. for U1, U2, U3, M1, M2, M3, G1, G2 where present). Indicate characteristic genus in each substratum with an up arrow or hat '^'. Must match characteristic growth form	Up to 5 dominant growth forms for each substratum. Indicate characteristic growth form with an up arrow or hat '^'. Must match characteristic genus	1 cover class code for each substratum	1 height class code for each substratum
	Example	<i>U1+ ^Eucalyptus coolabah,Casuarina cristata,Flindersia maculosa/Eucalyptus/^tree/7/r;M1 ^Acacia salicina,Alectryon oleifolius ,Acacia stenophylla, Acacia victoriae ssp. victoriae, Eremophila bignoniiflora/Acacia/^shrub/4/bi;M2 Eremophila longifolia, Muehlenbeckia florulenta/Eremophila/shrub/3/r;G1 ^Aristida ramosa, Astrebla squarrosa, Bothriochloa decipiens, Dichanthium sericeum, Enteropogon acicularis/Aristida/^tussock grass,forb,sedge/2/i</i>			

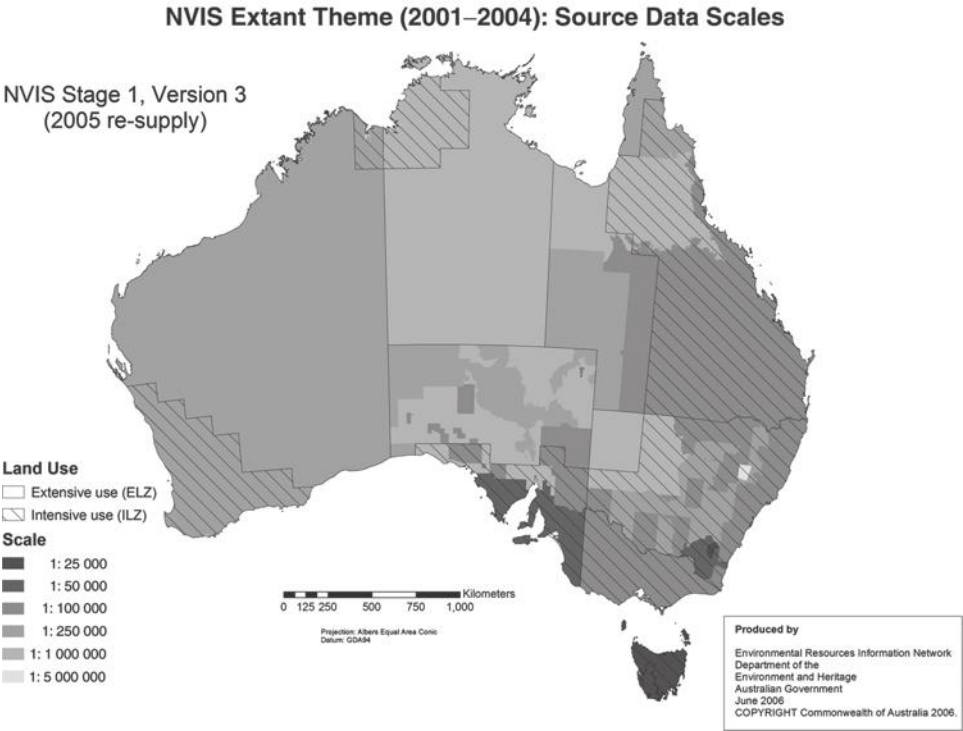


Figure 8.4 Coverage of the NVIS 2000 present vegetation and the scale gaps associated with the data set.

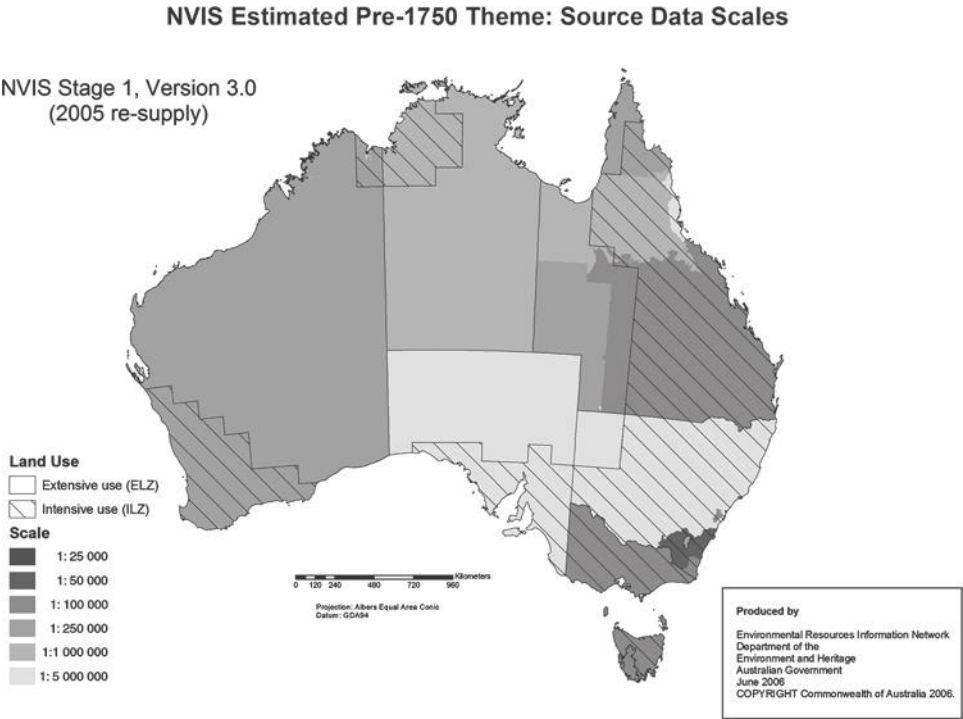


Figure 8.5 Coverage of the NVIS 2000 pre-European vegetation data set.

wet tropics in Queensland. Coarse-scale mapping (i.e. 1:1 000 000) is available for the Northern Territory and the area south of the Gulf of Carpentaria in Queensland. Obvious gaps in the ILZ occur where vegetation mapping is coarser than 1:100 000. These include the south-west and north-west of Western Australia, the north-west of the Top End of the Northern Territory, and most of New South Wales.

Future developments

Definitive vegetation types

Several states and territories have either developed or are developing lists of definitive vegetation types (i.e. association or subassociation). Once all lists are available, it will be possible to compile a national list of definitive vegetation types at a particular scale. However, access to such a list might still not produce a consistent national map at either the association or subassociation level because the detail of the classification needs to match the scale of mapping. In developing the NVIS (2000) data set, Thackway et al. (2001) showed that only a few jurisdictions and regions have mapping equivalent to the association level, although most states have field data that could be used to generate an association-level description for most vegetation types.

The systematic use and application of a definitive list of vegetation types (i.e. association and/or subassociation) will enable polygons and data sets to be compared. It will also enable the integrity of the original data sets to be maintained. When completed, this taxonomy should apply equally across multiple study areas and jurisdictions. The development and use of definitive vegetation types in regional and national maps will allow better incorporation of vegetation information into natural resource management, conservation, planning and research.

Updating type and extent

To date, mapping has focused on capturing a snapshot of vegetation at cartographic scales ranging from 1:25 000 to 1:1 000 000, with most mapping being done at 1:100 000 in the intensive land use zone (ILZ) and at 1:250 000 in the extensive land use zone (ELZ). In some landscapes subject to rapid change in land use (e.g. as a result of agricultural intensification, plantation development, urbanisation), vegetation type and extent can change from native to non-native and non-vegetated cover types over short times. Monitoring of this change is needed. Queensland has the only state-wide program for updating regional ecosystem maps on a regular basis (Neldner 2005). Regular updating will enable monitoring of broad trends in vegetation type, extent, use and condition.

Monitoring is more challenging than mapping (see *Chapter 30*). The trends in land use change are all likely to lead to an increase in demand for finer scale information. Little mapping of vegetation type and extent has been undertaken at cartographic scales between 1:25 000 and 1:50 000 because of the cost.

Monitoring frameworks

Recent vegetation-related developments and activities at the national level have established procedures for regularly updating information about Australia's vegetation. Authorities acknowledge the need for regular snapshots of Australia's vegetation cover, and they see the limitations of relying on existing data sets. For example, the National Forest Inventory aimed to report indicators of forest condition. This proved difficult because most information was collected for specific purposes with a variety of techniques and methods. Also, there is little information about privately owned land. As a result, new ways to map and

monitor Australia's forests have been proposed (Wood and Norman 2002). In particular, the Continental Forest Monitoring Framework has been developed to establish and maintain a sampling-based program for forest monitoring. It may be applied to all vegetation types (Norman et al. 2003).

The Continental Forest Monitoring Framework is designed to incorporate new technologies as they become available (e.g. developments in remote sensing at a range of scales). The Framework, still under development, has three interrelated tiers for data collection:

1. Tier 1 maps vegetation and land cover types along with canopy density using coarse-scale remote sensing.
2. Tier 2 utilises high-resolution remote sensing across a fairly large ($\geq 5\%$) but representative sample of the whole country. Tier 2 is integrated closely with Tier 3.
3. In Tier 3 a comprehensive set of attributes is directly measured periodically in the field across a relatively small ($< 0.1\%$) representative subsample of the Tier 2 sample.

In the longer term, NVIS will include site data from across Australia. This places new demands on field sampling and measurement. The widely used Walker and Hopkins (1990) system for vegetation description will need to be developed further to ensure consistency and rigour in data collection across Australia.

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Land use mapping

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Introduction

Until recently there has been little detailed mapping of land use at national and regional scales in Australia. Before the 1980s, land use information was generally derived from land system and soil mapping (e.g. Weston 1981; Western Australia Department of Agriculture 1985). Since then, public agencies have produced maps using well-established cartographic methods involving the interpretation of remotely sensed imagery, biophysical information, social and economic data and ground survey (e.g. Natmap 1980, 1982; Victorian Department of Water Resources 1989; New South Wales Soil Conservation Service soil erosion and land use map series 1983–91).

More recently a national set of land use data (1:2 500 000 scale) provided an overview of land use activities across the continent (Stewart et al. 2001). This set is based on coarse-scale satellite data (AVHRR) and Australian Bureau of Statistics Agricultural Census data combined with pre-existing finer-resolution data.

Land use mapping at catchment scale has now been completed through the Australian Collaborative Land Use Mapping Program. Nationally agreed methods have provided for cost-effective production, making best use of pre-existing land use information contained in sources such as cadastre (property-boundary information), public-land databases and land cover mapping.

Purpose

Changes to land use and land management have a major bearing on the condition of land and water resources. Developing responses to matters such as salinity, poor water quality and the maintenance of biodiversity involves investigation of land use, land cover and land management, and the trade-offs between various options. Predictive modelling is used and it requires data on current land use and land management at scales appropriate to the problems being addressed. Maps of current land use and alternative land use scenarios also help communities participate in proposed changes.

Key concepts in land use mapping

Reliance on remotely sensed data (satellite-based or airborne) for land use mapping often means there is confusion between the terms 'land use' and 'land cover'. Moreover, the distinction between 'land use' and 'land management practice' is also poorly understood. Land tenure and commodity information can also contribute to land use mapping.

- *Land cover* refers to the surface of the earth, including various combinations of vegetation types, soils, exposed rocks and water bodies as well as anthropogenic elements such as agriculture and built environments. Land cover classes can generally be distinguished by characteristic patterns in remotely sensed imagery. Land cover mapping at catchment scales has been completed for the agricultural areas of Australia (Barson et al. 2000).
- *Land use* is simply what the land is used for. Some land uses, such as agriculture, have characteristic land cover patterns. These generally appear in land cover classifications. Other land uses, such as nature conservation, are not readily distinguished by characteristic land cover patterns. For example, land use in which the land cover is woodland may either be for timber production or nature conservation.
- *Land management practice* is the means by which a land use outcome is achieved – the how of land use (e.g. cultivation practices such as minimum tillage and direct drilling). Patterns in land cover can relate to management practice and land use.
- A *commodity* usually refers to a product of agriculture or mining product that can be processed. Commodity information may relate to land use and land cover, particularly at finer divisions of classification. Data on agricultural commodities are available through the Australian Bureau of Statistics Agricultural Census.
- *Tenure* refers to the form of an interest in land. Some tenure types (e.g. pastoral leases or nature conservation reserves) relate directly to land use and land management practice. The Collaborative Australian Protected Areas Database (CAPAD), for instance, is a database of land tenure that provides annually updated information that ensures accurate and cost-effective description of conservation and natural environment land uses.

The Australian Land Use and Management Classification

A nomenclature and classification scheme for land use entails the ordering of land use in a systematic and logically consistent way. The Australian Land Use and Management (ALUM) Classification is based on a scheme developed by Baxter and Russell (1994) for the Murray–Darling Basin Commission. It was adopted as a suitable model for land use mapping in Australia by a Commonwealth–state workshop (Barson 1999), and has been revised several times as mapping has progressed.

The ALUM Classification is structured around five primary levels of land use in order of generally increasing levels of intervention or potential impact on the natural landscape (see Table 9.1). Water is included in the classification as a sixth primary class. Class definitions and agreed procedures and specifications for land use mapping at catchment scale are available in a regularly updated handbook prepared by the Bureau of Rural Sciences (2006).

The ALUM Classification framework is a structure to which attributes describing commodities or land management practices can be attached. Primary and secondary classes relate to land use (the prime use of the land defined in terms of the management objectives of the land manager). Tertiary classes can include commodities, commodity groups, land management practices or vegetation information. The classification is intended to be flexible so that new land uses can be accommodated as long as there is no conflict with other existing items. Water, although a land cover attribute, is included in the classification because of its importance for natural resource management, and the significance of water features as points of reference in the landscape.

Although tertiary-level data are valuable in many applications relating to natural resource management, the field time they require means they are expensive to collect. Mapping is usually completed to the tertiary level only where pre-existing data are available, or where tertiary-level information is of special interest to the mapping agency.

Table 9.1 Australian Land Use and Management Classification (version 6)

1 Conservation and Natural Environments	2 Production from Relatively Natural Environments	3 Production from Dryland Agriculture and Plantations	4 Production from Irrigated Agriculture and Plantations	5 Intensive Uses	6 Water
1.1.0 Nature conservation 1.1.1 Strict nature reserves 1.1.2 Wilderness area 1.1.3 National park 1.1.4 Natural feature protection 1.1.5 Habitat/species management area 1.1.6 Protected landscape 1.1.7 Other conserved area 1.2.0 Managed resource protection 1.2.1 Biodiversity 1.2.2 Surface water supply 1.2.3 Groundwater 1.2.4 Landscape 1.2.5 Traditional indigenous uses 1.3.0 Other minimal use 1.3.1 Defence 1.3.2 Stock route 1.3.3 Residual native cover 1.3.4 Rehabilitation	2.1.0 Grazing natural vegetation 2.2.0 Production forestry 2.2.1 Wood production 2.2.2 Other production	3.1.0 Plantation forestry 3.1.1 Hardwood production 3.1.2 Softwood production 3.1.3 Other forest production 3.1.4 Environmental 3.2.0 Grazing modified pastures 3.2.1 Native/exotic pasture mosaic 3.2.2 Woody fodder plants 3.2.3 Pasture legumes 3.2.4 Pasture legume/grass mixtures 3.2.5 Sown grasses 3.3.0 Cropping 3.3.1 Cereals 3.3.2 Beverage & spice crops 3.3.3 Hay & silage 3.3.4 Oil seeds 3.3.5 Sugar 3.3.6 Cotton 3.3.7 Tobacco 3.3.8 Legumes 3.4.0 Perennial horticulture 3.4.1 Tree fruits 3.4.2 Oleaginous fruits 3.4.3 Tree nuts 3.4.4 Vine fruits 3.4.5 Shrub nuts, fruits & berries 3.4.6 Flowers & bulbs 3.4.7 Vegetables & herbs 3.5.0 Seasonal horticulture 3.5.1 Fruits 3.5.2 Nuts 3.5.3 Flowers & bulbs 3.5.4 Vegetables & herbs 3.6.0 Land in transition 3.6.1 Degraded land 3.6.2 Abandoned land 3.6.3 Land under rehabilitation 3.6.4 No defined use	4.1.0 Irrigated plantation forestry 4.1.0 Irrigated hardwood production 4.1.2 Irrigated softwood production 4.1.3 Irrigated other forest production 4.1.4 Irrigated environmental 4.2.0 Irrigated modified pastures 4.2.1 Irrigated woody fodder plants 4.2.2 Irrigated pasture legumes 4.2.3 Irrigated legumes/grass mixtures 4.2.3 Irrigated sown grasses 4.3.0 Irrigated cropping 4.3.1 Irrigated cereals 4.3.2 Irrigated beverage & spice crops 4.3.3 Irrigated hay & silage 4.3.4 Irrigated oil seeds 4.3.5 Irrigated sugar 4.3.6 Irrigated cotton 4.3.7 Irrigated tobacco 4.3.8 Irrigated legumes 4.4.0 Irrigated perennial horticulture 4.4.1 Irrigated tree fruits 4.4.2 Irrigated oleaginous fruits 4.4.3 Irrigated tree nuts 4.4.4 Irrigated vine fruits 4.4.5 Irrigated shrub nuts, fruits & berries 4.4.6 Irrigated flowers & bulbs 4.4.7 Irrigated vegetables & herbs 4.5.0 Irrigated Seasonal horticulture 4.5.1 Irrigated fruits 4.5.2 Irrigated nuts 4.5.3 Irrigated flowers & bulbs 4.5.4 Irrigated vegetables & herbs 4.6.0 Irrigated land in transition 4.6.1 Degraded irrigated land 4.6.2 Abandoned irrigated land 4.6.3 Irrigated land under rehabilitation 4.6.4 No defined use (irrigation)	5.1.0 Intensive horticulture 5.1.1 Shadehouses 5.1.2 Glasshouses 5.1.3 Glasshouses (hydroponic) 5.2.0 Intensive animal production 5.2.1 Dairy 5.2.2 Cattle 5.2.3 Sheep 5.2.4 Poultry 5.2.5 Pigs 5.2.6 Agriculture 5.3.0 Manufacturing and industrial 5.4.0 Residential 5.4.1 Urban residential 5.4.2 Rural residential 5.4.3 Rural living 5.5.0 Services 5.5.1 Commercial services 5.5.2 Public services 5.5.3 Recreation and culture 5.5.4 Defence facilities 5.5.5 Research facilities 5.6.0 Utilities 5.6.1 Electricity generation/transmission 5.6.2 Gas treatment, storage and transmission 5.7.0 Transport and communication 5.7.1 Airports/aerodromes 5.7.2 Roads 5.7.3 Railways 5.7.4 Ports and water transport 5.7.5 Navigation and communication 5.8.0 Mining 5.8.1 Mines 5.8.2 Quarries 5.8.3 Tailings 5.9.0 Waste treatment and disposal 5.9.1 Stormwater 5.9.2 Landfill 5.9.3 Solid garbage 5.9.4 Incinerators 5.9.5 Sewage	6.1.0 Lake 6.1.0 Lake - conservation 6.1.2 Lake - production 6.1.3 Lake - intensive use 6.2.0 Reservoir/dam 6.2.1 Reservoir 6.2.2 Water storage - intensive use/farm dams 6.2.3 Evaporation basin 6.2.4 Effluent pond 6.3.0 River 6.3.1 River - conservation 6.3.2 River - production 6.3.2 River - intensive use 6.4.0 Channel/aqueduct 6.4.0 Supply channel/aqueduct 6.4.2 Drainage channel/aqueduct 6.5.0 Marsh/wetland 6.5.1 Marsh/wetland - conservation 6.5.2 Marsh/wetland - production 6.5.3 Marsh/wetland - intensive use 6.6.0 Estuary/coastal waters 6.6.1 Estuary/coastal waters - conservation 6.6.2 Estuary/coastal waters - production 6.6.3 Estuary/coastal waters - intensive use

minimum level of attribution

The principles that underpin the ALUM Classification approach include:

- *Level of intervention* – the classification is based on identification and delineation of types and levels of intervention in the landscape, rather than descriptions of land use based on outputs. Precedence is also given to the potential uses of the data for modelling over monitoring uses, and monitoring over descriptive uses.
- *Generality* – the classification is designed to provide for users who are interested in processes (e.g. land management practices) and outputs (e.g. commodities).
- *Hierarchical structure* – the structure provides for aggregation and disaggregation of related land uses, the addition of levels or classes and use at a range of scales.
- *Prime use and ancillary use* – some parcels of land are used in several ways simultaneously. A multiple-use production forest may have as its main management objective the production of timber, although it also may also provide conservation, recreation, grazing and water catchment services. Allocations to land use classes are based on the primary land management objective of the nominated land manager, and secondary uses can also be recorded.

Primary and secondary levels of the classification are described below. Tertiary levels are shown in Table 9.1.

1 Conservation and natural environments

Land in this class is used primarily for conservation purposes, based on the maintenance of essentially natural ecosystems already present. Little human intervention is involved, with the expected consequence of minor change to natural ecosystems. The land may be formally reserved by government for conservation purposes, or be conserved through other legal or administrative arrangements. Although areas may have multiple uses, nature conservation is the prime use. Some land may be unused as a result of a deliberate decision of the government or landowner, or as a result of circumstance.

- 1.1. *Nature conservation* – various forms of reserve, classified according to the Collaborative Australian Protected Areas Database (CAPAD) (Cresswell and Thomas 1997) together with other forms of conservation, including heritage agreements and voluntary conservation arrangements.
- 1.2. *Managed resource protection* – land managed primarily for the sustainable use of natural ecosystems classified according to CAPAD as well for traditional Indigenous uses.
- 1.3. *Other minimal use* – land that is largely unused either by decision or by circumstance. This includes natural areas used for military purposes or occasional livestock grazing (regular or semi-regular grazing is classified as 2.1). Unusable land such as cliffs and rock faces or degraded land under rehabilitation is also included.

2 Production from relatively natural environments

Land is used primarily for primary production based on limited change to the native vegetation. The structure of the native vegetation generally remains intact despite deliberate use, although floristics may have changed markedly.

- 2.1. *Grazing natural vegetation* – grazing of native vegetation by domestic stock with little or no attempt at pasture modification. Some change in species composition might have occurred, but the structure of the native vegetation will remain essentially intact.
- 2.2. *Production forestry* – commercial production from native forests and related activities on public and private land. Environmental and indirect production uses associated with

retained native forest (e.g. prevention of land degradation, wind breaks) are included under *Conservation and natural environments*.

3 Production from dryland agriculture and plantations

Land is used mainly for primary production, based on systems of dryland farming. Native vegetation has largely been replaced by introduced species through clearing, the sowing of new species and the application of fertilisers or volunteer species.

- 3.1. *Plantation forestry* – plantations of trees or shrubs established for production or to protect the environment and resources, including farm forestry. Where planted trees are grown together with pasture, fodder or crop production, class allocation should be made on the basis of prime use (with or without multiple-class attribution).
- 3.2. *Grazing modified pastures* – pasture and forage production, both annual and perennial, based on a significant degree of modification or replacement of the initial native vegetation. Land under pasture at the time of mapping may be in a rotation system so that at another time the same area may be cropped. Land in a rotation system should be classified according to the land use at the time of mapping.
- 3.3. *Cropping* – crop production, including arable crops and pasture or other rotation systems under cropping at the time of mapping. Fodder production is treated as a crop if mechanically harvested. Tertiary classes can be based on commodities or commodity groups that relate to Australian Bureau of Statistics (ABS) agricultural commodity categories.
- 3.4. *Perennial horticulture* – crop plants living for more than 2 years that are intensively cultivated, usually involving a high degree of nutrient, weed and moisture control. Tertiary classes can be based on ABS horticultural commodity categories.
- 3.5. *Seasonal horticulture* – crop plants living for less than 2 years that are intensively cultivated, usually involving a high degree of nutrient, weed and moisture control. Tertiary classes can be based on ABS horticultural commodity categories.

4 Production from irrigated agriculture and plantations

This class includes agricultural land uses where water is applied. It includes land that receives only one or two irrigations per year, as well as areas that rely on irrigation for much of the growing season. Land parcels should be assigned to this class if infrastructure for irrigation is located in the parcel, although the land may be temporarily unused or put to alternative uses such as grazing.

- 4.1. *Irrigated plantation forestry* – irrigated tree or shrub plantations established for production or environmental and resource protection purposes, including farm forestry.
- 4.2. *Irrigated modified pastures* – irrigated annual and perennial pastures where production is based on a significant degree of modification or replacement of the native vegetation. This class includes land in a rotation system that at other times may be under arable crops.
- 4.3. *Irrigated cropping* – irrigated cropping, including land in a rotation system that at other times may be under pasture.
- 4.4. *Irrigated perennial horticulture* – irrigated crop plants living for more than 2 years that are intensively cultivated, usually involving a control of nutrients, weeds and moisture.
- 4.5. *Irrigated seasonal horticulture* – irrigated crop plants living for less than 2 years that are intensively cultivated, usually involving a control of nutrients, weeds and moisture.

5 Intensive uses

Land is subject to substantial modification, generally in association with closer residential settlement, commercial or industrial uses. Intervention may be such as to remodel completely the natural landscape, the vegetation, surface and groundwater systems and the land surface.

- 5.1. *Intensive horticulture* – intensive forms of plant production, including shadehouses, glass-houses and hydroponic cultivation.
- 5.2. *Intensive animal production* – agricultural production facilities such as feedlots and piggeries.
- 5.3. *Manufacturing and industrial* – factories, workshops, foundries, and construction sites, including the processing of primary produce (e.g. sawmills, pulp mills, abattoirs).
- 5.4. *Residential* – land used for residential purposes. If rural land is managed as a hobby farm, it should be assigned to 5.4.2 ‘Rural residential’. The size of rural allotments or local government zoning plans may be useful indicators of rural residential land use.
- 5.5. *Services* – land allocated to the provision of commercial or public services resulting in substantial impact on the natural environment. Where services are provided on land that retains natural cover, an appropriate classification under Section 1: ‘Conservation and Natural Environments’ should be applied.
- 5.6. Utilities
- 5.7. Transport and communication
- 5.8. Mining
- 5.9. Waste treatment and disposal – waste material and disposal facilities associated with industrial, urban and agricultural activities.

6 Water

Although water features are normally classified as land cover types, their inclusion in the land use classification is essential because of their importance for natural resource management and as points of reference in the landscape. At the secondary level the classification identifies water features, both natural and artificial. Tertiary classes relate to intensity and purpose of use. Water classes do not necessarily exclude other land use classes. Generally, water classes should take precedence, so that, for instance, a lake in a conservation reserve will be classed as 6.1 ‘Lake’ or 6.1.1 ‘Lake – conservation’ rather than 1.1 ‘Nature conservation’.

Applying the ALUM Classification

Experience has shown there may be uncertainty in the application of the ALUM Classification when several land use classes apply to a parcel of land or an appropriate class is not available. Alternatively, it might not be possible to determine land use from available data or field observations confidently. Some suggestions for handling areas of uncertainty, and promoting consistency in application of the classification, are as follows:

- *Hierarchical ordering* – where a particular land use cannot be allocated to a class at a given level in the classification because of ambiguity, the allocation is made to the more generalised class at a higher level of the hierarchy. If the problem is the absence of an appropriate class at a particular level of the classification hierarchy, then a new class at that level may be created.
- *Determining prime use* – the prime use of land is determined on the basis of the primary management objective of the land manager. This means, for example, if there is a developed residential area within a national park, this residential area would be classed as 5.4.1 ‘Urban residential’ because the prime use of this area is urban or residential, not nature conservation.

- *Handling multiple uses* – in some instances more than one land use may apply to a particular parcel of land. Common examples include grazing in native forests reserved for timber production, opportunity logging in grazed woodlands, grazing on land under rehabilitation, and strip cropping. If prime use only is recorded then important information about other uses of the land may be lost. Ancillary, secondary or multiple uses of the land may be recorded as a part of the land use mapping process.
- *Temporal change* – the frequency of land use change varies considerably. Some land uses may be fairly stable, remaining in place over decades or more. In other cases, land use turnover may be rapid – this applies in particular where land use change is geared to seasonal or annual cycles (e.g. rotations of pastures with arable crops). Where rapid turnover occurs, the temporal mismatch between source data and field verification poses difficulties. The currently agreed principle is to assign land use classes to land parcels at a particular point in time. This means, in the case of crop–pasture rotations, that the assigned land use will be either a modified pasture class (3.2) or a cropping class (3.3). The particular rotation regime (which may be critically important in natural resource management) is an issue only for attributing a land management practice.
- *Source information* – more than one source of information may be available for assigning land use to a parcel of land, and these may conflict. Generally, metadata will indicate which information source should take precedence. The order of reliance should be: 1 field observation; 2 expert knowledge (e.g. agriculture extension officer); 3 ancillary data; and 4 evidence from the adjoining or local areas.
- *Attaching additional information* – a wide range of additional land information (particularly information about land cover and land management practices) can enhance interpretation of land use. Important ancillary information of this kind may be attached to the framework for classifying land use as supplementary attributes.
- *Managing uncertainty in class allocation* – during mapping, making immediate decisions about class allocation may be difficult if land use is not clearly identified or several classes could apply. The need for hasty decisions is avoided if working codes are used to record special circumstances. If retained as a part of the land use data set, this also will enable class allocations to be revised. The use of working codes is not a basis for avoiding formal class allocation, nor a substitute for thorough checking in the field.

A look-up table has been constructed to translate the ALUM Classification into: the interim Australian and New Zealand Land Use Code (ANZLUC) (Standards Australia 1999); the Western Australian Standard Land Use Classification (WASLUC) (Western Australian Land Information System 1998); and several international land cover or land use classifications. Comparison of the results for catchment-scale maps shows that WASLUC and ANZLUC contain many classes for intensive uses, but relatively few for agricultural uses.

Survey methodology

The recommended procedures for land use mapping and the creation of land use data sets based on the ALUM Classification are described and represented (Figure 9.1). The mapping procedures are described in full by Bureau of Rural Sciences (2006).

Data collation

The first stage involves collation of existing data sets containing land use information. Key data sources are satellite imagery and aerial photography, cadastre, and state and territory digital

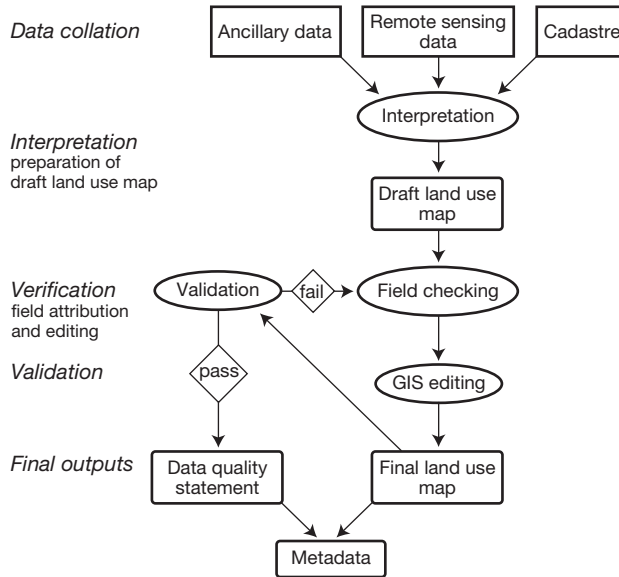


Figure 9.1 Land use mapping procedure.

topographic mapping. Other data sets from state and territory agencies relate to land capability, forestry, vegetation, conservation reserves, land cover, planning and land management.

Interpretation

This stage involves interpreting land use from several sources including remote sensing, cadastral information and the ancillary data sets noted above. A land use mask is created from these sources. Appropriate land use codes are assigned, and draft land use maps are prepared for verification and field checking. Land use codes are assigned according to the ALUM Classification. Steps include:

1. the initial interpretation of imagery, aerial photography and land use information contained in other source data sets into appropriate ALUM land use classes and the creation of a land use mask data set with coded land use attributes
2. entering interpreted data details into the metadata table
3. checking the interpreted classes against remotely sensed data
4. capturing new features and assigning land use codes.

Verification and editing

Verification of draft land use maps includes annotation of field maps on the basis of expert advice and field checking and editing land use tracts. Personnel familiar with local patterns of land use need to be involved in this process. Steps in the verification and editing process include:

1. planning field-mapping and data-collection routes
2. creating field maps – (a) land use with cadastral boundaries; and (b) remotely sensed data with cadastral boundaries
3. meeting extension officers, annotating land use maps and revising field plans on the basis of the information acquired

4. field checking
5. attributing polygons with appropriate codes and annotating for editing.

Independent validation

For land use mapping, validation is concerned primarily with assessing thematic accuracy or attribute accuracy under the ALUM Classification. Validation may be approached in several ways. Focus may be placed on assessing the accuracy or reliability of the interpreter. Alternatively, the assessment may be designed to measure the accuracy of mapping in comparison with the real world at a particular time. The cost of the validation should remain reasonable in relation to the cost of producing the land use data set.

The recommended validation procedure compares attribute information in the land use data set with information obtained from high-quality data not used previously for base mapping (field survey or large-scale aerial photography). Field validation is carried out shortly after completion of mapping and is designed to give users a general indication of attribute accuracy. The number of sample points used in validation limits the confidence that can be placed in the accuracy of classes covering small areas. Validation is done by a team that has not participated in compilation of the land use data. The recommended procedure (Denham 2005) involves:

- exclude classes which can be determined reliably from tenure
- determine the number of points for remaining classes on the basis of area of land use and number of polygons
- create a set of random points for each class and interpret their land use
- construct an error matrix comparing mapped classes at sample sites with independently observed classes and calculate the total, user's and producer's accuracies for the map and their 90% confidence intervals.

The specifications are met if the lower bound of the confidence interval is greater than 80%. If the mapping fails this test, the area is re-mapped and the validation procedure repeated.

Output production

This stage includes finalisation of land use data, metadata, validation reporting and quality assurance. The quality assurance involves evaluation of metadata, spatial data characteristics, classification accuracy, data-transfer standards and validation. Quality is assured independently and reported in a data quality statement that remains with the data set (Bureau of Rural Sciences 2006).

Data and metadata specifications

The recommended data structure for land use data sets (Table 9.2) allows land use polygons to be assigned information about the prime land use (the ALUM code and associated descriptor), the primary information source (scale, date, reliability), secondary or 'ancillary' land uses (optional), and a working code (optional) that relates information about particular land use and classification issues.

When used to describe vector data, data resolution is the size of the smallest geographical entity that can be mapped at a given scale and still effectively communicate the entity's location and shape – it is the minimum mapping unit. Minimum data resolution is not absolute, but is determined on the basis of the scale of the information sources from which the data set is derived, the purposes of the data, the intended final mapping scale, data processing requirements and cartographic conventions. Land use data sets are from many sources and they are

Table 9.2 Recommended data structure

Attribute	Format ^A	Description	Example
Lu_code	C 8 8	Land use code	4.5.1
Lu_description	C 36 36	Description of land use	Irrigated fruits
Source_scale	C 8 8	Scale of source data	1:100 000
Source_date	D 8 10	Date of spatial feature e.g. image date, air photo date, ancillary data date	xx/xx/xxxx
Reliability	B 4 5	Reliability of attribute	1 = field mapping/local knowledge 2 = ancillary dataset 3 = air photo 4 = SPOT imagery 5 = Landsat ETM/TM 6 = other
Luc_date	D 8 10	Date of land use code	xx/xx/xxxx
Multiple_uses	B 4 5	Ancillary uses associated with a parcel of land – ALUM codes	1 – n (link to lookup table)
Work_code	B 4 5	Project working code – description of project specific situations and classification decisions	1 – n
Xxxxxx	xxxxx	Other attributes as required	

^AARC/INFO coverage format (ESRI 2005).

useable in a wide range of applications. It is important that data resolution standards do not exclude useful high-quality information contained in input data.

Standards for data resolution for land use mapping should be flexible and constrained primarily by the resolution of source data. The recommended data structure (see previous paragraphs) allows source and scale information for each feature to be retained in the attribute field, with information about particular spatial standards also detailed in the metadata. Data resolution specifications for features may vary within a single land use data set according to the standards that apply to source information. This can result in the production of nested data sets (e.g. small irrigation areas mapped at 1:25 000 within broad-acre agriculture mapped at 1:100 000).

Standards for data resolution may also vary according to the significance of features being mapped. Intensive land use features that are readily discriminated may be mapped with higher resolution standards than extensive, low-intensity land uses. Minimum standards, nevertheless, promote consistency in the way land use features are represented. Data-resolution specifications for land use data sets are suggested in Table 9.3.

Table 9.3 Recommended data resolution

	Size on map	Equivalent size in field at a map scale of		
		1:50 000	1:100 000	1:250 000
Surface area of the smallest mapped feature	2 x 2 mm	1 ha	4 ha	25 ha
Minimum width for linear features	1 mm	50 m	100 m	250 m

Metadata comprise structured summaries of information that describes the data. They include characteristics such as the content, quality, currency, access and availability of the data. Current specifications for land use data sets derive from the ANZLIC set of core metadata elements (ANZLIC 2001, see *Chapter 26*).

Land use mapping progress

At the national level, land use mapping at a scale of 1:2 500 000 has been completed for 1992–1993, 1993–1994, 1996–1997, 1998–1999, 2000–2001 and 2001–2002. This work used Advanced Very High Resolution Radiometer (AVHRR) satellite data and ABS Agricultural Census data for agricultural land uses, combined with pre-existing finer resolution data (mainly 1:250 000 scale) for other uses.

Nationally consistent land use mapping at catchment scale has now been completed or commenced for the Australian continent – at cartographic scales of 1:250 000 in the pastoral zone, 1:100 000 in broad-acre cropping regions, 1:50 000 in the coastal areas and 1:25 000 in peri-urban and irrigation areas (Figure 9.2). Data can be accessed via www.brs.gov.au/landuse.

The cost of mapping at 1:100 000 scale ranges from A\$2.50/km² to A\$10.00/km² depending on the extent of the mapping and intensity of land use. The relationship between mapping scale, intensity of land use and mapping effort (cost) is illustrated in Table 9.4.

Data obtained so far have been used in many applications. In Western Australia they have been used to plan flight lines for a locust control program, and in developing programs to prepare for both Newcastle and Foot and Mouth disease. In Victoria, the Environment Protection Authority uses land use data to plan sediment and nutrient management for the Gippsland Lakes. The data were also used for land use planning by the Gippsland Local Government Network Program. In South Australia data have been used to help calculate emergency services taxes. The Bureau of Rural Sciences and the Queensland Department of Natural Resources and

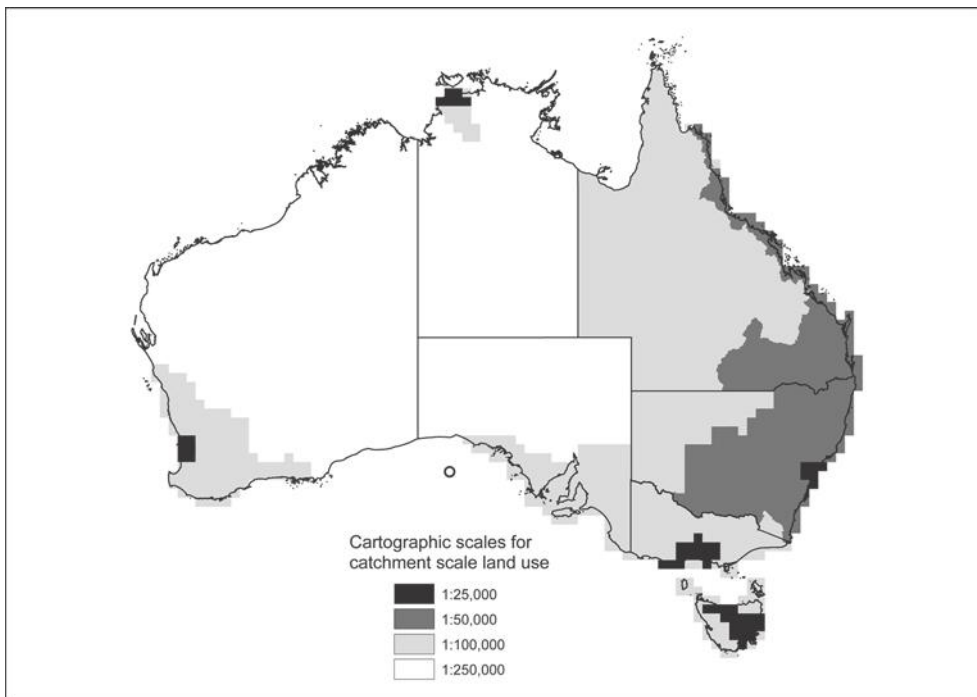


Figure 9.2 Cartographic scales for catchment scale land use.

Table 9.4 Mapping effort (cost) in relation to scale and intensity of land use

	Scale of mapping			
	1:25 000	1:50 000	1:100 000	1:250 000
	Approximate person-days per area equivalent to			
	1:100 000 map sheet	1:100 000 map sheet	1:100 000 map sheet	1:250 000 map sheet
Low intensity mapping low population, large farms, little land use change, few roads, uniform land use			10	10
Medium intensity mapping broadacre, predominantly dryland farming, smaller farms, future intensification of land use expected			15	
High intensity mapping high population density, small farm size, rapid land use change, multiple uses within farms, horticulture, high road density	30	25	20	

Management have used land use data to identify risks of groundwater pollution associated with horticulture in the Bowen district, and to develop methods for collecting information on the use of agricultural and veterinary chemicals (Baskaran et al. 2001).

Future directions

To date, mapping has focused on capturing a snapshot of land use at scales ranging from 1:50 000 to 1:250 000. In peri-urban and coastal regions, land uses can change rapidly in response to urbanisation pressures, and in other regions there have been recent increases in the extent of irrigated agriculture, vineyards and cereal cropping. Map sheets for regions undergoing substantial change need to be updated regularly; this can be done by incorporating changes detected via aerial photography or other spatially explicit data into the existing data sets, updating the metadata and validating the new land use map. Intensification of land uses is likely to lead to demands from users for data at finer scales. So far, little mapping has been undertaken at 1:25 000 (generally the most appropriate scale for mapping irrigation and peri-urban areas and for local government planning) because of cost. Regular updating will enable trends in land use to be monitored.

Predictive modelling of salinity, water quality and other natural resources for catchments will also require information about land management practices. In 2004, state agencies, Australian government departments, industry groups and scientific organisations convened to discuss the need for a national approach to the collation and mapping of land management practices. It was agreed to develop a national categorisation and information system for land management practices (Land Use Management Information System – LUMIS). State agency partners are undertaking pilot studies in 2007 to develop methods for mapping these practices.

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Remote sensing with air photography

D Dent

Introduction

Vertical images of the landscape have underpinned land resource survey since the pioneering surveys of Stewart and Christian in northern Australia during the 1940s (Bourne 1931, Christian and Stewart 1952). In the beginning, black-and-white air photographs were used, with overlapping scenes to allow stereoscopic viewing. This technique is still in use: a testament to its power and robustness. It combines an optical image of features that are immediately recognisable, three-dimensional stereoscopic views, and the human capacity to detect and analyse subtle visual patterns.

Many huge developments in image acquisition from both aircraft and satellites have provided information useful for predicting and mapping land and soil properties. Imagery can be used for manual interpretation, just like traditional air photographs, although usually without the advantage of stereoscopic viewing. However, when images are draped over shaded digital elevation models the relationship to the underlying terrain becomes apparent.

The new digital techniques lend themselves to quantitative analysis. This means the inherent subjectivity of manual interpretation can be augmented by more objective analyses of, for example, the spectral signatures of various features within an image. Computerised methods of image analysis are sophisticated, but the human brain remains important.

Both manual and quantitative image interpretation have roles in survey; each has strengths and weaknesses. The choice of imagery and method of interpretation – or combination of types and methods – depends on availability, the landscape and the objectives of the survey. This chapter and the next three review air photography, reflectance and temporal analysis of remotely sensed imagery, and gamma-ray spectroscopy.

Air photographs

Air-photo interpretation became an integral part of land resource surveys in the 1940s, especially for reconnaissance of large, sparsely populated areas such as northern Australia. It facilitated surveys of a scale, detail and extent that could be achieved only by earth-bound methods at great expense. However, it requires skill and experience because the view of the ground and its cover is unfamiliar, and yet what lies below the surface must be inferred from this view. Its usefulness also depends on the strength of relations between the visible features and the characteristics of interest. Air-photo interpretation is now well established for survey and has been described by many authors. The description below draws upon Dent and Young (1981, see *Chapter 3*) and Dalal-Clayton and Dent (2002, see *Chapter 3*).

The most common kind of air photography is that taken vertically from aircraft flown along parallel flight lines. The photographs are now usually in colour, and they are taken with

60% overlap between successive scenes to enable stereoscopic viewing. The usual format is a print, 230 mm square. The most useful scale for interpretation of land cover, soils, hydrology and geology is 1:25 000. The resolution obtainable is finer than 0.01 mm on the print, which is equivalent to less than 0.25 m on the ground.

Photographs can also be enlarged for use at the farm and town scale. Photo-scanning equipment can cheaply record and store images digitally, and enlargements of up to 5–10 times the scale of the original can be printed. However, enlargements add little to interpretation – the stereoscopic effect is lost on enlargement – and fine detail is better seen by binocular magnification.

One can prepare large-scale base maps from air photographs by fixing ground control points (e.g. using global positioning system, GPS, equipment with better than 1 m accuracy) which enables one to correct the geometry of the original image.

A distinct advantage of detailed photographs is that people can easily recognise features belonging to their own localities without special training, and so they can participate in local survey and planning. A disadvantage is that many prints may be needed to show the area of interest. Sequential prints can be pasted together to create a *photomosaic*, but this is made difficult by the distortion of scale around the margins of each print, especially in hilly country. The more costly *orthophotomaps* get around this problem by planimetrically rectifying each component photograph. In addition, they may have contours, spot heights and other base map information overprinted.

Standard black-and-white *panchromatic* photographs (Figure 10.1) represent the visible spectrum on a grey scale. True-colour photography gives no extra detail but provides a more recognisable image. Infrared film extends the range of sensitivity into the near-infrared: the image looks like an ordinary photograph but has added tonal contrasts. Water absorbs infrared radiation strongly and so appears black; however, chlorophyll has a high reflectance, and different species, different stages of growth and crops under stress are all more easily distinguished on infrared photographs. These contrasts are heightened by *false-colour* photography – in which all the colour bands are shifted to make room for the infrared: blue is filtered out, green is printed as blue, red as green, and infrared as red. The result is that different species, stages of growth and densities of vegetation appear as different shades of red or pink. The initial appearance can seem strange, but one soon becomes accustomed to it. False-colour photography is especially valuable in surveys of wetlands, forests and rangelands.

Using air photographs

Air photographs have two principal uses in soil survey, and these are of equal status.

1. As *base maps*, for planning routes, navigation in the field, and recording the location of field observations and the boundaries of mapping units. For these purposes, photographs are invaluable, not only in the obvious situation of unmapped country, but also in flat or sparsely settled areas that lack roads, houses, field boundaries and other details which would appear on topographic maps (see *Chapter 18*).
2. For *interpretation*, of soil, vegetation, land use, water resources and so forth where they are sources of primary information. Field observations reveal more about conditions at a site but photographs show spatial distributions much more effectively.

One of the first steps in a survey is to find out what photographic cover exists and to commission more if necessary. Recent photography is preferable for route-finding and location, especially where there have been recent changes in land use, although good use may still be made of older cover if costs dictate. In recently afforested areas, photography flown prior to afforestation is invariably more useful for recognition of soil patterns.



Figure 10.1 Black-and-white air photo of the Aitape land system on the coast of the Bismarck Sea, north-west Papua New Guinea. The landscape consists of low to high hill ridges on limestone and calcareous conglomerate in the coast plain (Haantjens et al. 1972).

Having obtained the photographs, the next substantial task (rarely mentioned in manuals of interpretation) is to identify precisely what areas they cover. Flight cover diagrams are often illegible, lacking in base detail, or missing. Make a complete print lay-down. Draw up your own cover diagram, giving run numbers, print numbers at the ends of runs, and orientation and sketch in the principal roads, rivers and settlements. Write names of these features on the backs of the photographs and add north arrows if necessary. If a base map exists, it is worth marking the principal points of all photographs on it.

Put each run into an envelope labelled with run and print numbers. Make sure that every photograph carries enough information to enable anybody to restore it to its correct envelope. Time spent in sorting, labelling and locating the photographs pays off in time saved and irritation avoided at later stages of the survey.

Properties of air photographs

You should know the fundamental properties and limitations of the air photograph to avoid pitfalls and unrealistic expectations.

- The photograph is an image of the land surface on which differences in surface reflectance of light appear as differences in colour and tone.
- The photograph is not planimetrically correct. That is, scale varies across the print (unless it is an orthophotograph). Variations in scale are caused first by the projection, scale being accurate only close to the centre of the photograph; second by relief, with hilltops lying closer to the camera than valleys (and so appear at a larger scale); and third, tilt of the aircraft. For interpretation and for use in the field, these variations are unimportant, and the photograph can be treated as a map. But for transfer of boundaries from photograph to map, the variations are significant and simple tracing can lead to errors.
- Through stereoscopic viewing of adjacent pairs, an interpreter can learn a great deal about landscapes that are not apparent on a single print.

Photo-interpretation depends on recognising differences in reflectance together with relief. The differences are apparent in tone, texture, pattern, shape and relief.

Tone is the shade of grey, ranging from black to white. Rock and bare soil (unless black) tend to appear as pale tones; wet soil is darker than dry soil. Coniferous trees appear darker than broad-leaved trees. Water absorbs visible light, so usually appears dark unless muddy or shallow.

Texture is the fine pattern of contrast in colour and tone, at a scale too small for the individual elements to be distinguished. Bare mudflats give a smooth texture, forest canopy a moderately rough one. Most crops have a characteristic texture; unfortunately, small grain crops (e.g. wheat, barley) have similar textures to grassland, but can be distinguished by tone, varying with the season or stage of growth.

Pattern is regular variation in tone at a scale at which the individual elements can be seen. Examples of features that produce clear and characteristic patterns are: orchards, vineyards, badlands, termite mounds and gilgai. Features that show a pattern on detailed-scale photographs become texture at less detailed scales.

Shape refers to individual features not repeated as a pattern.

Variations in these features are combined with information on relief.

Relief visible in air photographs consists of relative height differences within the area of the overlap of a single stereoscopic pair. Where ground control is established, absolute heights and accurate contours can be mapped by photogrammetry. Such accuracy is unnecessary for general-purpose land resources survey but it is likely to be needed for irrigation planning and many engineering works. Advances in laser altimetry and terrain analysis are replacing photogrammetry (see *Chapter 6*).

Interpreters usually identify landscape features by convergence of evidence, without giving conscious thought to the separate properties listed above. They will usually need to refer to these properties, however, when describing to someone else (or even rationalising to themselves) how a particular landscape feature can be identified: for example, 'the lighter tone is some special kind of grass, possibly indicating shallow ferricrete', or 'the almost regular pattern of spots on flat ground indicates gilgai'.

Scale

Useful photograph scales in land resource survey range from 1:50 000 to 1:5000 (Table 10.1). It is obvious that detailed scales allow more to be seen and smaller mapping units to be delineated. Set against this are four disadvantages:

Table 10.1 Air-photograph scales

	Scale	Area covered by one whole print (km ²)	Working area on one print ^A (km ²)	Number of prints per 100 km ²	Ground equivalent of 1 mm (m)	Ground equivalent of 1 cm ² (ha)
Very detailed	1:5 000	1.3	0.8	240	5	0.25
Detailed	1:10 000	5.2	3.3	60	10	1
	1:20 000	21	13	15	20	4
Semi-detailed	1:25 000	33	21	10	25	6.25
	1:30 000	47	30	7	30	9
	1:40 000	84	53	4	40	16
	1:50 000	131	84	2.4	50	25
Reconnaissance	1:1 000 000	34 000	20 000+	0.005	1000	10 000

^A The 'working area' is that covered by a single print after omitting overlap with adjacent runs and with next-but-one prints in a run (i.e. the area on which boundaries are drawn on alternate prints).

1. *Number and cost of prints.* The number of prints needed to cover a given area is four times greater for every doubling of scale (i.e. 1:50 000–1:25 000). Flying costs increase at somewhat less than this rate, since the cost of getting airborne is met only once.
2. *Difficulty in seeing landscape patterns.* Detailed-scale photographs allow only a small land area to be viewed stereoscopically at one time and as a result repeating patterns of landforms or other features are hard to identify – the geomorphological equivalent of being unable to see the wood for the trees.
3. *Superfluous detail.* Some interpreters find it impossible to resist drawing boundaries wherever they can be seen. If the photograph is on a much larger cartographic scale than the intended map, they will cover it with lines which cannot be verified in the field, represented on the map, or both.
4. *Time taken over interpretation.* Through a combination of the above reasons, the time taken to interpret increases almost proportionally to the number of prints (i.e. 3–4 times as long if the scale is doubled). Useful information obtained (i.e. landscape or soil boundaries of practical significance) increases very much slower.

For these reasons, a good general rule is to choose the smallest cartographic scale compatible with the accuracy or fineness of detail required on the final map. Except in reconnaissance surveys, this will usually be 2–2.5 times the map scale.

For reconnaissance surveys of large areas, a photographic scale of about 1:40 000 is best. Landform units and other spatial patterns can be seen readily. It is reasonable to interpret 4–8 pairs of photographs, and thus 100–200 km², in a day. It is rather difficult, but still possible, to use 1:40 000 prints to find your way in the field. Even though the intended map may be at 1:250 000 or smaller, the boundaries on photographs at scales smaller than 1:40 000 are packed too close together.

Photograph scales of 1:20 000 or 1:25 000 are suited to a wide range of soil surveys in which photo interpretation is balanced by a substantial amount of field survey. Broad landform patterns can still be identified (though less easily than at smaller cartographic scales), while detailed land facets can be delineated at the same time. Where required, fine detail can be picked out under $\times 3$ magnification. Tracks and individual trees can be seen, invaluable for planning routes and locating observation sites.

Scales of 1:10 000 or larger are suited to detailed, special-purpose surveys, including surveys of peri-urban areas. Landform patterns are lost, except where they are intricate, and interpretation needs to be based on landform elements or detailed vegetation characteristics. Often such photographs are used primarily as base maps for intense field survey.

Equipment for photo interpretation

The only essential tool for photo interpretation is a good mirror stereoscope. A moving table and $\times 3$ binoculars are desirable, while a zoom stereoscope or similar instrument is a luxury (albeit a pleasant one) unless photo interpretation is a major component of total survey effort. The essential design feature in a mirror stereoscope is that the whole of the stereoscopically common area is easily visible at once. A moving table allows different parts of the view to be brought under binocular view without disturbing the stereoscopic alignment.

A zoom stereoscope gives a continuous change in magnification while remaining more or less in focus; a cheaper alternative is to add $\times 8$ binoculars.

For field use, two kinds of stereoscope are available. The conventional lens-type pocket instrument produces a $\times 2.5$ magnification but only 60-mm wide strips down either side can be viewed without bending the print. The field mirror stereoscope, which comes with its own folding magnetic photo table, can view the whole stereoscopic overlap by moving the instrument, but is more expensive and also less convenient to use.

Subsequent transfer of boundaries from photograph to map can be done in two ways: by plotter or by sketchmaster or similar instrument. The stereoplotter is an advanced photogrammetric instrument that rectifies scale errors on the photograph. Its principal use is in the production of orthographic base maps. It requires a skilled technician to operate it. If your survey organisation does not possess a plotter, the cost of subcontracting should be written into the contract.

The precision of mapping units or their boundaries might not always justify photogrammetric accuracy. Provided a topographic map exists at a scale not too dissimilar from that of the photograph's, a competent job can be done with sketchmaster or stereosketch, matching features on the base map (e.g. tracks and rivers) to those on the photograph.

Application of air photographs in land resource survey

The applications of air photographs may include any, or all, of the following:

- to make the base map – by photogrammetry
- for the main photo interpretation, assessment of the landscape and drawing of provisional boundaries prior to field survey
- to plan field operations – this can include selection of routes, traverse lines, variation in sampling density, omission of certain areas altogether (e.g. mountains) and in some cases marking of individual observation sites in advance; locating good transects along catenas is particularly valuable; the use of photographs to choose representative sites is widespread (see *Chapter 19*)
- to navigate in the field, and to locate observation sites – take trouble to locate these carefully (e.g. by pacing from identifiable detail or through use of a GPS receiver), mark immediately with crayon or a pinprick ringed in crayon, and add the observation number to the photograph on its reverse side
- for revision, or post-field interpretation – many of the provisional boundaries may need to be erased if they turn out to have no significance for the purposes of the survey; except in reconnaissance surveys, there will be new distinctions identified in the field not previously noted on the photographs and once these are known, they can sometimes be extrapolated on the photographs (e.g. as slightly darker tones or small changes in slope or vegetation, or, failing that, you might simply draw a line that follows the same position in a catena)

- for presentation – the final map is sometimes published on a photographic base; publication in this form limits the map to symbols, preventing use of colours unless by transparent overlays; the product is less artistically pleasing than a coloured map but a photographic base of good definition is of more value to users, who can locate familiar features directly on the ground.

Interpretation

One fundamental fact cannot be emphasised too strongly: the photograph is only an image of the land surface, and you cannot see what lies beneath. Two important consequences follow:

- interpretation must be based on what can be seen, namely landforms, vegetation and possibly land use
- usefulness of the interpretation for soils, water resources or specific hazards (e.g. salinity or erosion) depends on how clearly the relationships between these visible features and the object of interest can be established in the field.

In many cases the soil cannot be seen at all, as it is covered by forest, grass or crops. Where ground is bare, either because of cultivation or aridity, it is only the surface skin that reflects light into the camera. Differences in surface reflectance may be caused by colour, texture or moisture content of the topsoil; usually darker tones indicate heavier texture or moister soil. There are special circumstances where this can prove of value, such as on depositional landscapes under arable use (e.g. prior streams in the Riverina of New South Wales).

The features of the landscape visible on air photographs are landforms (including surface water), vegetation or other land cover, the tone of bare soil, and human structures. Interpreters sometimes base their inference mainly or entirely on landforms (making a deliberate decision to exclude other features in the interest of having a uniform basis) or on landforms and vegetation combined. Circumstances calling for the use of vegetation alone are flat or swampy landscapes. Land use and land cover need to be used with discretion, while soil reflectance is locally important. Generally, however, the interpreter makes use of whatever can be seen on the photograph, regardless of its origin; this may include features with a distinctive photographic appearance, the meaning of which may not be known at the time.

Landforms

Stereoscopic interpretation of air photographs has been the key to integrated survey, the land system first being defined as ‘an area or group of areas, throughout which there is a recurring pattern of topography, soils and vegetation’ (Christian and Stewart 1952) and identified in the first place by this pattern on air photographs. Although land system survey generally works by stepwise subdivision of the landscape, some geomorphologists have applied the opposite approach of building up mapping units either by combining single parameter maps or by combining geomorphologically related sites into larger groupings. The latter approach still begins with air photograph interpretation to identify representative traverses and, by interpretation of landform units on air photographs, completes the process by extending the sites characterised in the field to the wider landscape.

Landform units can be distinguished at a wide variety of scales, ranging from subcontinental to the parts of a single slope (see Table 3.2). Speight (1990) provides the standard scheme used in Australia and it was developed with air-photo interpretation in mind (e.g. Speight 1974, 1977). Detailed air-photo interpretation will identify landform elements (typically 20–500 m in extent) and, at a broader scale, landform patterns (typically 1 km to >10 km in extent). Refer to Speight (1990) for the defining attributes and the agreed Australian procedures for describing landforms.

Geomorphological photo interpretation is by no means limited to the description of ground surface forms in a static sense. Landforms, soils and vegetation have evolved together. The processes responsible for landforms also strongly influence parent materials and soils; hence recognition of landforms in dynamic terms (with respect to both past and current processes) is equally important. This aspect is particularly significant in depositional landscapes (e.g. an alluvial plain). Where the processes responsible can be inferred with confidence, a range of soil properties and the broad soil pattern can be predicted by interpretation of surface features, in the first instance from air photographs. The use of a conceptual model in no way substitutes for systematic field investigation but, by anticipating important characteristics of soils, regolith and hydrology, the model can guide field investigations. Sampling sites may be chosen to characterise well-defined areas and to establish the characteristics of doubtful areas, and many soil boundaries may be drawn from their surface expression.

Vegetation

Vegetation is often mapped in its own right (see *Chapter 8*). It can also be used for mapping soil and land resources in three circumstances:

- where there are expanses of little-disturbed natural vegetation
- on depositional landforms
- where land is farmed.

Where the vegetation has not been greatly disturbed by management, it can be a sensitive guide to the pattern of soils, since vegetation responds to small differences in, for example, moisture, thickness, pH and salinity of the soil. This is particularly the case in dry regions and at dry times. However, these responses can be complicated by human activity through cutting, burning and grazing. This does not mean that vegetation ceases to be of value as an indicator, but it does mean that interpretation must be more circumspect.

In depositional landscapes, such as alluvial plains and tidal flats, small variations in elevation can be significant in terms of soil morphology, chemistry and physical properties of the soil, its hydrology and, consequently, its land use potential. While these differences may be too small to distinguish directly in air photographs, use can be made of the response of vegetation to associated changes in hydrology, salinity and sedimentation. A good example is the use of different mangrove communities to map acid sulfate soils (Dent 1980). The kinds of units distinguished are floodplains, river and creek levees, swamps, relict stream channels, stream bars, silted lagoons and tidal flats. The relationship between vegetation communities, landform units and significant soil and land attributes must then be established by fieldwork.

Land use

Air photographs have a major role in mapping land cover and land use (see *Chapter 9*) because land uses can be readily distinguished. However, land use is a fickle guide to land and soil properties because sharp boundaries in land use, although possibly indicating a change of soil or hydrology, are just as likely to be caused by settlement history, land tenure or local infrastructure (e.g. the provision of irrigation, stock water or domestic water supply).

Ground surface

Differences in the appearance of bare ground can be valuable guides to soil properties in some situations. Rock outcrops can be readily identified. In deserts, sand dunes, playas and saline depressions can be distinguished. In depositional landscapes, especially under arable use, it is usually possible to identify prior streams and relict stream channels, levees and so on. These features usually have a different topsoil texture and water content from the surrounding plain, giving contrasting reflectance.

Procedure

Photo interpretation depends mainly on the existence of direct links between landform and soil and land properties. While interpretation can be described in terms of recognising colour, tone, texture and pattern, and the different spectral reflectances of vegetation or water, and patterns of relative relief, it calls not so much for knowledge of photographs as of landscapes. We find information on the photographs according to the knowledge that we bring, be it geomorphology and surface processes, ecology, hydrology or experience of field survey.

Procedures for air-photo interpretation depend upon the purpose and scale of the survey and the type of landscape. However, there are some steps in common.

1. Lay out the photographs for the entire area to get an impression of the main landscape patterns – if possible in conjunction with satellite imagery, which provides the big picture, and gamma radiometrics that reveal distinctive parent materials and patterns of erosion and deposition (see *Chapter 13*).
2. Work rapidly through all the photographs using a stereoscope, identifying and making descriptions of photo interpretation units, based in the first place on landforms and using vegetation patterns where necessary. Note photographs on which units are well expressed.
3. Do the main interpretation by working more slowly across the photographs, drawing boundaries between units. Use a wax-type pencil to draw directly on alternate photographs. This does not damage the photographs and can be easily erased. Start by drawing boundaries around prominent features such as hills, swamps and dunes and only then proceed to more uncertain features.
4. There are two possibilities for handling joins between photographs: either interpret each photograph separately and then reconcile boundaries where they cross the edges of photographs, or transfer boundaries crossing the edges on to the next photograph. The latter course is better.
5. Review the interpretations. It will probably be necessary to accept some rather arbitrary boundaries where one map unit fades into another (i.e. where there is a progression of intergrades) or where there are areas that do not fit the scheme of units devised (i.e. extra grades). This reflects the reality of landscapes.
6. Last, fill in the details, such as slope units if required. In general, this is best left until after fieldwork.

The ease with which units can be identified varies from landscape to landscape. In some the main features of the landscape stand out so clearly that they dictate what can and should be mapped. More commonly, a level of generalisation is required that captures the main features of the landscape without creating an impractical number of mapping units. Where it is difficult to decide whether to split apparently different features into separate units or lump them together, the rule is to split during the early, pre-field stages of a survey (as long as the units distinguished can be shown at the scale being used). Later, where differences are found not to be significant, they can be eliminated. During post-survey revision, the best course is the opposite approach: lumping together features where there is uncertainty about the significance of any differences.

Relationship between photo interpretation units and map units

Photo interpretation gives us a way of predicting land characteristics and qualities of interest to those managing the land without having to visit everywhere in the survey area. To be useful, the units delineated, confirmed and revised by fieldwork need to carry information about these land characteristics and qualities. A unique asset of air-photo interpretation is that it can reveal catenary or hydrological relationships between adjacent facets of the landscape. For instance, in developing a salt hazard map, it might be possible to deduce and delineate intake, transport and discharge zones.

At reconnaissance scales, the units are usually based on broad relief features (e.g. a floodplain, a breakaway and footslopes). Interpretation of air photographs, together with other remotely sensed imagery, is the primary means of delineating these map units. The role of fieldwork is to sample these units to describe the patterns of soils and other land attributes that they encompass. The sampling density is sparse so the information carried by map units is a general description of the land resources and how they vary within each unit (e.g. along catenary sequences).

At more detailed scales, photo interpretation makes use of more subtle evidence, often in combination, to determine mapping units. Major breaks in slope are usually associated with changes in soil, hydrology and vegetation. Less dramatic changes in slope, or surface tone and texture indicating change in vegetation, may or may not be significant. In any case, field observations will be necessary for confirmation. Often a combination of landform and vegetation that provides a good indicator of soil and land attributes in one area might be quite misleading in an adjacent area, so thorough field checking is always necessary.

As map scale becomes more detailed, map units are expected to carry more specific and accurate information. This means an increasing reliance on field survey to determine both the boundaries of map units and what lies within them. Nevertheless, photo interpretation provides the context for spatial prediction of land attributes and, in every case, can save time and improve accuracy.

Photo interpretation may prove difficult in two situations. Where the landscape is blanketed by thick forest, the canopy softens relief to such an extent that it hides first-order valleys, so that only the main hills and swamps can be distinguished. In intensively managed lowlands, especially under irrigation, air-photo patterns are dominated by field boundaries and crops that make underlying patterns hard to distinguish.

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Remote sensing with imaging spectroscopy

A Held

Introduction

This chapter introduces principles of imaging spectroscopy. It outlines how small differences in the spectral reflectance of organic and inorganic compounds can be used to differentiate, quantify and map a broad range of landscape materials.

Fundamentals of imaging spectroscopy

Digital remote sensors commonly placed on board Earth-observing or planetary-exploration satellites record reflected or emitted radiation in specific, well-defined wavebands of the electromagnetic spectrum (EMS). This radiation can be used to identify the types of materials on the surface of the Earth, other planets or stars. Most of the visible light occurs in a narrow part of the EMS (Figure 11.1).

Remote sensing provides access to terrain information in wavelengths outside the visible spectrum, allowing events and materials that are not directly visible or distinguishable in normal vision to be observed. The general principle is the same as laboratory spectroscopy. There, materials are illuminated with a source of radiation of known spectral characteristics and brightness, and the amount absorbed, transmitted or reflected by the material is used to identify it. The absorption of radiation by materials results mainly from the effects of photons on chemical bonds in molecules. The technique has been used in laboratory analysis for more than 100 years and, in astronomy, for identifying the composition of stars, and is now much used in industrial manufacturing, food production and medicine (see *Chapter 17* for applications to rapid soil measurement).

Some well-known systems of satellite sensors used for Earth observation (e.g. Landsat MSS and TM, Spot HRV) detect light in broad regions (also called bands) of the visible (400–700 nm), near infrared (700–1300 nm), and, in the case of Landsat, also in the shortwave infrared (1300–3000 nm) and thermal (10 000–12 000 nm) bands. Although most of these sensors use reflected solar radiation, some detect radiation emitted from the ground in the thermal infrared. All these sensors are passive detectors, and they contrast with active sensors that emit energy to illuminate the surfaces of interest. The latter transmit radiation towards the ground and then measure the reflected radiation after alteration by the different objects or surfaces. Radio Detection and Ranging (RADAR) is a well-known active system operating in the microwave part of the spectrum. Laser Detection and Ranging (LIDAR) operates at optical frequencies using laser pulses. Because of the EMS frequencies involved, most optical and thermal passive systems provide information on the chemical nature of the surfaces from which they originate, whereas the RADAR and LIDAR systems provide information on the

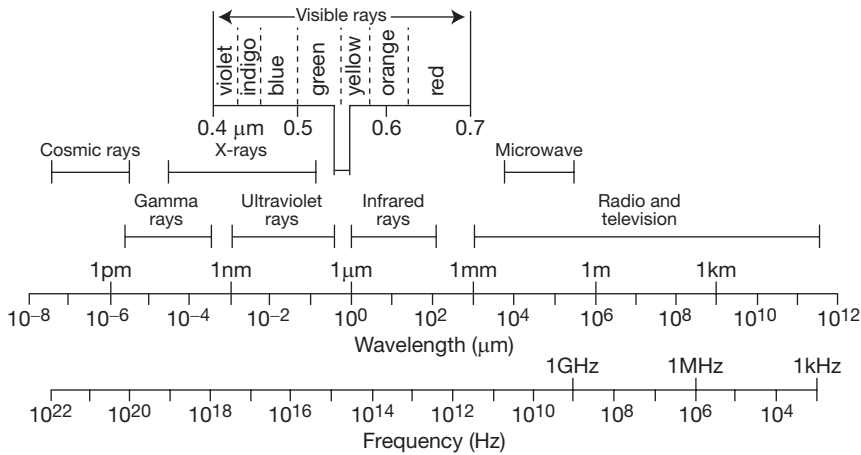


Figure 11.1 The electromagnetic spectrum (after Harrison and Jupp 1989).

three-dimensional nature and structure of the objects they encounter (e.g. detection of elevation). This chapter focuses on optical passive sensors.

Early spectrometers on satellites and aircraft, designed mainly for geological exploration and monitoring weather, consisted of a single line of adjacent spectrometers with broad spectral sensitivity in several spectral bands. The forward motion of the platform would then allow a two-dimensional spectral measurement of the Earth's surface to be generated (Figure 11.2).

Satellite sensors in use today, such as those on the Landsat TM and SPOT HRV satellites, are essentially of this nature, and they collect two-dimensional images of the Earth's surface in up to seven bands. Each two-dimensional digital image is composed of thousands of picture elements (pixels), each of which contains information on the radiance measured at several wavelengths. When extrapolated to the ground, the pixel size or spatial resolution in most commonly used satellites ranges from 30 m to 1000 m, whereas in airborne systems the pixel size can be as small as 0.10 m or 0.20 m, depending on the altitude of the aircraft and the field of view of the instrument. Satellite data of the Earth's surface have been collected since the mid-1970s, and a good archive is now available for investigation of changes in vegetation cover and land use.

Data acquisition

Sensor systems: airborne and satellite

It did not take long for imaging spectrometers on satellites or aircraft to increase in sensitivity and in the number of spectral bands they could record. New instruments now collect reflected radiation in 100 or more spectral bands – effectively a continuous reflected radiation spectrum – and the data are now becoming much more accessible. The advantages of some of these spectrometers (so-called imaging spectrometers or hyperspectral sensors), as opposed to the previous multispectral sensors with only 4 to 7 broad spectral bands, is that they are much better calibrated and more stable, allowing the user to apply true spectroscopy principles to better distinguish small chemical differences between objects (Curran 1994). In addition, more precise corrections for the effects of absorption by atmospheric gases are easier than for multispectral systems.

In the late 1980s and early 1990s, the management and analysis of the prolific data in the images from hyperspectral systems was hindered by a lack of adequate computer software,

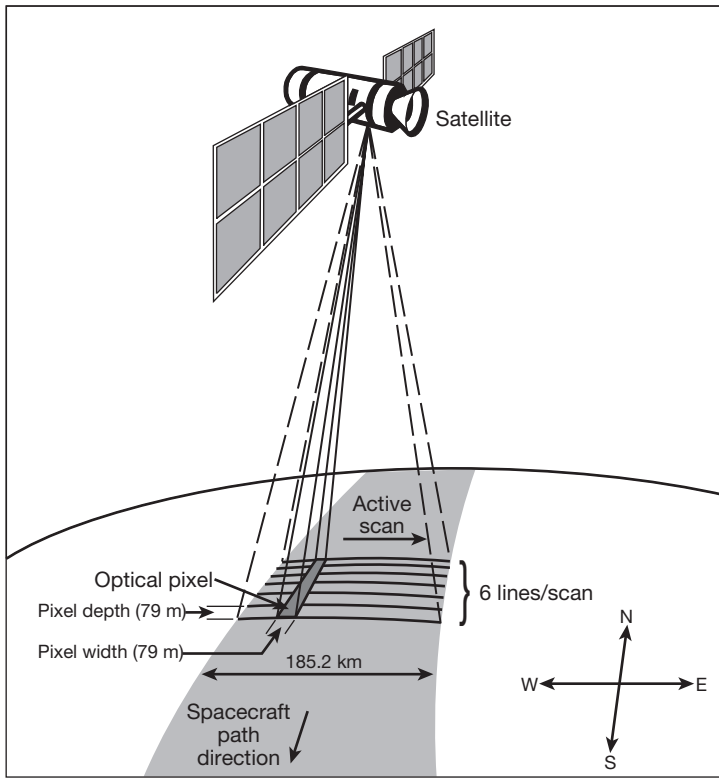


Figure 11.2 Diagram of a typical Earth-observing satellite (Landsat Multi-Spectral Scanner, MSS) (after Harrison and Jupp 1989).

inadequate processing power and storage capacity. Today the required software is commercially available, and most remote-sensing laboratories use standard personal computers that can easily handle large hyperspectral image files. While initially used mainly for mineral exploration and geological mapping (e.g. Hunt and Ashley 1979; Clark et al. 1990), the advantages of this technology for environmental monitoring has been widely recognised. It is now used in studies of vegetation dynamics (e.g. Miller et al. 1991; Ustin et al. 1993), vegetation biochemical composition (e.g. Wessman 1989; Martin et al. 1997), plant species discrimination (e.g. Clark et al. 1995) and soil mapping (Baumgardner et al. 1985; Hill and Schütt 2000).

Table 11.1 lists multispectral and hyperspectral systems in operation today, along with their general specifications.

Advantages and disadvantages of different systems

Airborne versus satellite systems

Once you have selected the right type of sensor (multispectral versus hyperspectral) for a given application, you have to choose between airborne or satellite systems. Satellite systems have the following features:

- cheap for low-resolution to medium-resolution spatial data
- little information and radiometric calibration in individual pixels
- discounts in price are often available for historical time-series of data over same region
- cheap to process data because file sizes are small

Table 11.1 Characteristics of some airborne and spaceborne optical sensors in use

Sensor name	Airborne or satellite	Country/agency/company	Spectral range Wavelength (nm)	Number of bands	Ground resolution (m)
Landsat 7	Satellite	NASA/USGS	450–12 500	7	30 (60 m, thermal)
SPOT	Satellite	France/Spot Image – Raytheon Australia	500–1750	4	20
DMSI	Airborne	Specterra Services	400–900	4	0.5–2.5
Casi	Airborne	Canada – Itres/ Ball AIMS	410–925	228/19	0.8–5
Hymap	Airborne	Hyvista Corporation	400–2543	59	3–5
Ikonos	Satellite	USA/Space Imaging	500–700	1	1
			400–1000	4	4
Modis	Satellite	USA/NASA	405–14385	36	250–1000
DAIS	Airborne	Germany/DLR	400–2500	72	5
Hyperion	Satellite	USA/NASA	400–2500	220	30

- advanced processing and image classification can be expensive because of cloud contamination and low radiometric quality.

Airborne data have the following, often complementary, features:

- considerably larger cost per unit area than satellite data
- information content per unit area is much larger because of the higher resolution and larger number of spectral bands
- aircraft and pilot costs are fixed, regardless of sensor on board
- costs of acquisition of advanced sensor data (e.g. hyperspectral) are becoming competitive with air photography
- data processing and analysis requirements vary depending on levels of processing, atmospheric correction, data quantity and spatial accuracy (root mean square, rms, of 3 m or better)
- when compared with standard field sampling supported by air-photo interpretation, hyperspectral scanner data can be more cost-effective in some applications (e.g. mapping coastal habitat: Malthus and Mumby 2003).

Overall, airborne systems allow for greater spatial resolution and are more flexible in responding to special events or natural disasters. Airborne systems often contain more advanced sensors, provide image data at higher spatial resolution, and can collect data under uniform clouds. However, satellites provide more stable platforms, even though spatial resolution is generally lower, and can cover larger areas more rapidly and at less cost per unit area. These systems also have fixed overpass times and can collect data routinely.

Suppliers

Table 11.2 lists the major suppliers of remotely sensed data in Australia. Arrangements for supply change, however, as companies come and go, new satellites are launched, and systems fail or are decommissioned.

Table 11.2 Major organisations providing remotely sensed data in Australia

Airborne multispectral and hyperspectral		
Digital Video	SpecTerra Systems	< http://www.specterra.com.au >
Daedalus 1268	Air Target Services	< http://www.airtargets.com.au >
Hymapt	HyVista Corporation	< http://www.hyvista.com >
Satellite multispectral and hyperspectral		
Landsat ETM	ACRES (Geoscience Australia)	< http://www.auslig.gov.au >
SPOT	SPOT	< http://www.raytheon.com.au >
ASTER	NASA/JAXA	< http://asterweb.jpl.nasa.gov >
ALOS	Geoscience Australia	< http://www.ga.gov.au >
QuickBird	SKM	< http://www.skm.com >
IKONOS	Space Imaging	< http://www.aamhatch.com.au >
MODIS	Geoscience Australia	< http://www.ga.gov.au >
Hyperion	USGS	< http://eo1.usgs.gov/index.php >

Internet addresses verified 21 March 2007.

What do the data show?

Hyperspectral data quantities are large, often between 200 megabytes and 500 megabytes per image file. A set of data can be conceived as a cube or slab in which the data have as many bands as there are columns (x-coordinates) and rows (y-coordinates) of information. The data for a single pixel are represented as a series of brightness values, one for each spectral band, and together they characterise the continuous spectrum. A hyperspectral image is composed of millions of spectra (i.e. one spectrum per pixel) representing various surface chemical features covering the area of interest.

When first received from the suppliers on disk or tape, digital image data are normally in a binary format, ordered by lines and bands, and expressed as digital numbers (DN) of brightness between 0 and 254 in the case of the traditional sensors such as Landsat TM or as many more brightness levels (giving greater precision) in more sensitive systems. In some cases, suppliers use predetermined calibration data to convert the images into 'at-sensor radiance' data in radiometric units (e.g. $\mu\text{W nm}^{-1} \text{sr}^{-1} \text{cm}^{-2}$). The data are usually corrected for atmospheric conditions, converted into 'target-leaving radiance' units, and normalised by the irradiance illuminating the target. They are then converted into reflectance units and further analysed (Figure 11.3).

When used for baseline mapping, hyperspectral imagery is commonly transformed into 'classification images', which show, in colour codes, the spatial distribution of different vegetation or soil features.

For the end user, classification is a simple matter of interrogating the data, and the main advantage of imaging spectrometers is their capacity to provide much finer and richer data, allowing discrimination and mapping of subtle differences in surface chemistry.

In many instances, pixels are larger than the objects of interest, so that the resulting spectral signals in the images are mixtures of spectra. If we assemble the spectra of pure materials into a spectral library, then the mixed-pixel signatures can be decomposed into the main signatures of the native material. The relative proportions of component materials for each pixel can then be calculated. This 'un-mixing' has been used to explore for minerals and to detect foreign materials hidden in large pixels (e.g. for military applications).

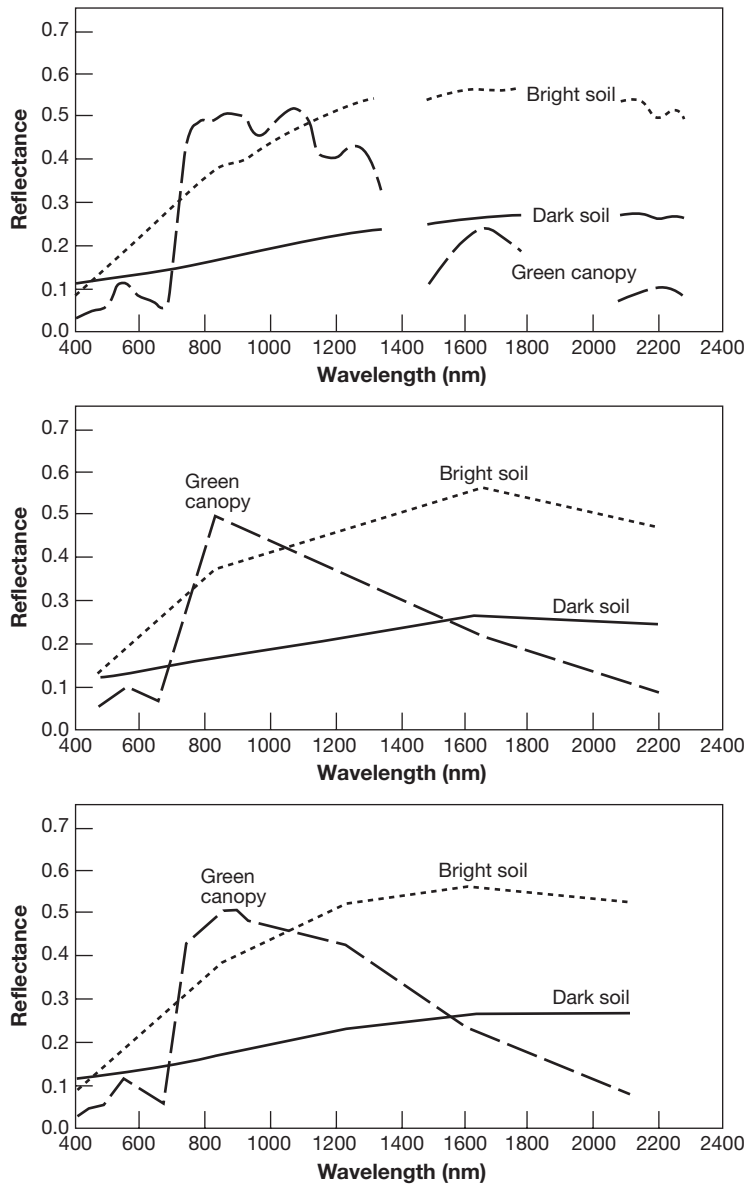


Figure 11.3 Typical reflectance spectra of green vegetation and two contrasting soil colour types, in this case a sugarcane crop, measured (a) with a hand-held full-range (400–2500 nm) Analytical Spectral Devices (ASD) spectroradiometer; (b) and (c) as would be measured by the Landsat TM and MODIS sensors respectively.

Spectral reflectance of vegetation and soil

To understand the advantages of hyperspectral sensors in the remote sensing of vegetation and soil, it is useful to appreciate how reflectance signatures for vegetation and soil arise.

For leafy vegetation, when light strikes a leaf, some is absorbed, a portion is transmitted through the leaf, and the rest is reflected back. For soils, light is reflected by the top few micrometres, except where the surface is very granular. These reflected signals, when analysed,

provide information on foliar chemistry or soil composition. Whereas the basic green colour of canopy reflectance is clearly detectable from sensors, such as those on the Landsat TM or MODIS satellites (which can also be used to find exposed soil patches), there are fine features of leaf chemistry or soil mineralogy that can only be detected with high spectral resolution (hyperspectral) sensors (see reflectance comparisons, Figure 11.3).

Only a small proportion (~10%) of light in the visible spectrum (400–700 nm) is reflected after almost total absorption by photosynthetic pigments (mainly chlorophylls and carotenoids). Green vegetation reflects much more radiation between 680 and 750 nm, which is commonly termed the ‘red edge’, and is caused mainly by the combination of strong chlorophyll-a absorption and internal light scattering in the leaf. This sharp increase in reflectance has been a key for developing greenness indices such as the Normalised Difference Vegetation Index (NDVI) and the Simple Ratio (SR), as they are composed of reflectances measured in the red (670–690 nm) and near infrared (750–800 nm), where the contrast caused by chlorophyll absorption in the 550–690 nm range, is large. Use of time-series of NDVI to monitor vegetation responses to weather or change in land use at regional and continental scales is described in Chapter 12. Changes in the inflection point of this red edge can indicate plant stress (e.g. Rock et al. 1996; Merton 1999). In wavelengths longer than 700 nm, reflectance is dominated by internal light scattering and light absorption by water, cellulose, lignin and leaf proteins.

At the whole-plant level, characteristic reflectance is also influenced by canopy structure, the geometry of illumination from the sun, and the spectral features of branches, background soil and litter. Changing the illumination angle geometry will give rise to changes in the reflected radiation and its spectral characteristics. For this reason, special care is required when comparisons are made between sites and, for a single site, between times. At the canopy level, spectral indices such as NDVI or SR exhibit a curvilinear relationship with increasing leaf area as a result of the overlap of leaves in canopies. Although it depends on leaf angle distribution and chlorophyll concentration, the NDVI for most vegetation types saturates at a leaf area index (LAI) exceeding 3–4. This is a problem for detecting early stress or phenological change with broad-band greenness indices in dense forests, where LAI is often as much as 10: the NDVI or spectral reflectance would not show a clear change until the canopy lost much of its leaf area as a result of the stress. However, with the advent of hyperspectral imaging, changes in concentrations of some pigments and other leaf chemicals can be measured more directly (see *Measurements of spectral reflectance of plants and other land-based materials*), suggesting that this technology should enable us to detect early signs of stress or phenological change even before changes in broad-band greenness and leaf area are detected.

Soil characteristics

Reflectance from soil is related not only to its mineral content, but also to wetness and organic matter content. In general, soil spectral signatures are much less dominated by peaks and troughs (Figure 11.3) and reflectance generally exceeds those of plants in the short-wave infrared region (1000–2500 nm). Water in soil has a strong influence on reflectance across the full spectrum – the wetter the soil the darker it appears. Reflectance spectra of moist soil contain the familiar absorption features at 970 nm, 1200 nm and 1770 nm caused by liquid water absorption: this is also a feature of green plant material. Iron minerals influence reflectance in the 700, 900 and 1000–1100 nm regions (Baumgardner et al. 1985), while organic matter has a similar effect on total reflectance as water content. However, organic matter content also changes the general shape of spectra, rather than introducing sharp, clearly identifiable absorption features like those from iron, calcium and clays.

Most studies that evaluate the use of hyperspectral sensors for soil mapping have focused on relatively sparsely vegetated semi-arid or seasonally sparse Mediterranean regions. Despite the difficulty of identifying specific absorption features associated with organic matter content, Hill and Schütt (2000) could map organic matter content and erosion features in Spanish and French soils using imaging spectrometry and spectral analysis. Similarly, Palacios-Orueta and Ustin (1998) and Palacios et al. (1999) in the Santa Monica Mountains of Southern California showed how well imaging spectrometers and associated analysis could characterise soil. Little has been done along these lines in Australia, in part because of past difficulties in accessing hyperspectral imaging systems. However, such systems are now more readily available as both local airborne sensors or from space (e.g. NASA EO-1 Hyperion).

Terrain variables, and aspects of vegetation condition and openness of canopy measured by high-resolution remote sensing, have been used to predict soil physical and chemical characteristics under forests (e.g. Skidmore et al. 1997; Coops et al. 1998). More direct geophysical methods and spectroscopic techniques with hyperspectral data have provided more precise measures of the composition of visible soils (e.g. Clark et al. 1990; Hill and Schütt 2000).

Field measurements and validation

Field spectrometry

Precise measures from multispectral or hyperspectral sensors on board aircraft or satellites need to be supported by ground-based measurements of the spectral reflectance of selected targets, and also of the spectral and geometric characteristics of the incident light reaching the target. Several computer packages can, to some extent, correct imagery for atmospheric conditions. Nevertheless, to remove the effects caused by atmospheric absorption, further corrections are needed: at least one field measurement taken at the same place as recorded in an image. You will also need to characterise the types of materials in the sampled region. Remote sensors and field systems should be cross-calibrated at least every six months.

When very large areas are mapped from satellites or aircraft, characterise strategically selected field sites in detail. It is good practice to include measurements of pseudo-invariant features (PIFs). These are uniform areas of sufficient size that can be identified in the satellite or airborne images and then used for additional calibration, or for assessment of the accuracy of the atmospheric correction.

In summary, field measurements made for remote-sensing fall into four main categories:

1. spectral measurements of incident radiation
2. spectral measurements of reflected radiation by sample surfaces and materials, including PIFs
3. measurements of weather to characterise the general environment around and above the target
4. additional measurements on tissue or soil to characterise further the target's physical or chemical properties – these are used to develop quantitative maps of surface chemistry.

Measurements of spectral reflectance of plants and other land-based materials

The spectral signatures of targeted plant species, soils, rocks and PIFs need to be recorded in a standard way with the correct reference reflectance panels. Consider the following when doing these measurements.

Hand-held spectroradiometers measure radiance reflected from the target back to the sensor, so to calculate reflectance, an additional measurement of the incident irradiance reaching the target is needed. The reference reflectance panels need to reflect incident light

efficiently, and more specifically, ensure the same amount of light is reflected in all directions (i.e. it is lambertian). The most common materials used for reflectance panels are barium sulfate or the Teflon®-based Spectralon®. Barium sulfate is fairly cheap and can be used, together with a good quality transparent lacquer, to produce an excellent surface that is white, reflective and near lambertian in behaviour. Spectralon® can be purchased either as a white powder in 'baked' form, or as highly compressed wafers. This material is nearly 100% reflective throughout the visible, near infrared and short-wave infrared range and is a very good laboratory standard. For operational use, build a small 0.5 m × 0.5 m barium sulfate panel, or use a calibrated clean piece of white canvas. If you use canvas, you need to estimate the relevant conversion factors for each waveband for conversion back to the barium sulfate or Spectralon® reflectance, before normalising against the target radiance to obtain reflectance.

When measuring the reflectance spectra, make sure the sun is shining on the target to the right or left of the line of measurement between the target and the spectroradiometer. This avoids hotspots or specular reflections.

Measure the sun's reflectance at midday. Avoid specular effects where direct sunlight effectively contaminates the reflected signal, especially over water. Minimise the effects of radiation coming from other nearby objects and maximise the signal reaching the spectroradiometer. Point the instrument at the target at an angle no larger than ~32 degrees away from vertical (nadir). This ensures the reflectance signature is similar to that detected by the airborne sensor.

The relationship between the distance to the target and field-of-view of hand-held spectroradiometers is important. Ensure the target of interest fills the instrument's field-of-view. For instruments with a field-of-view of 15 degrees, measure radiance in the range 0.3–0.5 m from the target if it has a diameter of 0.75 m. Make sure you know the real field-of-view of the spectroradiometer. You can determine it experimentally, but if an instrument has a field-of-view of 15 degrees, then assume it to be 10–12 degrees to avoid the influence of neighbouring objects.

When collecting spectral signatures of plant canopies or whole plants, collect also spectral signatures of other materials, such as underlying soil, litter and wood, in case the signature from the leaves in the canopy needs to be un-mixed from other signatures.

Note other variables that may influence either the irradiance reaching the target, or the reflectance of the target itself. Variables such as temperature and atmospheric humidity can influence the physiological state of plants (e.g. water stress) and their reflectance. Atmospheric variables and the relative positions of the sun and sensors are also important for subsequent corrections.

Measure vegetation reflectances under the natural canopy (ideally the intact canopy). This is difficult in tall forests, and there are other options. For instance, some large, dense-canopy branches can be sampled and measured over inert backgrounds. Alternatively, find younger individuals in clearings or more accessible locations. These can be measured with the assumption that their spectral signature does not change significantly from that of fully grown individuals. Another possibility is to extract the signatures directly from the atmospherically corrected images, provided that pixels are small enough to include pure parts of single tree canopies and their exact position is known. The modeller believes that the intrinsic signature for any plant should be possible to model from its components of leaf, wood, soil and litter. Methods for sampling vegetation signatures are still being developed, and agreed procedures have not been established for all vegetation types. In summary, use the procedures described above, but be careful to document ancillary data and describe the specific method in detail. See additional details in Aspinall et al. (2002).

Data processing

Suppliers of image-processing services

Traditionally, much of the analysis of remotely sensed imagery was carried out in the research laboratories of public agencies (e.g. university geography departments, CSIRO, land survey agencies). Many private companies now specialise in acquiring data, making maps, and adding value to remote sensing data. In Australia, suppliers of hyperspectral data analyse images for clients or, alternatively, subcontract research groups to do more sophisticated analyses.

Making the supplied data useful for land resource survey

Once the digital image data are downloaded from the airborne or satellite sensors, or purchased from commercial vendors, base processing is first required. This usually entails the following: radiometric correction for atmospheric and sensor-calibration factors, masking of cloud-affected areas, and geo-rectification to geographical coordinates. Some suppliers might have already processed the imagery (and even applied atmospheric correction). During atmospheric correction, data are converted from at-sensor to target-leaving radiances. At this point, the data can be used either for physically-based modelling and estimating material concentrations or for classifying regions into different ground materials or vegetation types. When normalised by the incident irradiance, data are transformed into reflectance units and can then be used for classification purposes. This commonly entails comparing the observed reflectance values in the imagery to ground-based measurements made of known, typical species or often pure materials. Unfortunately, image pixels, even as small as $1\text{ m} \times 1\text{ m}$, are seldom composed of pure materials or single plant species – they represent mixtures of spectral signatures. For this reason, techniques of analysis have been developed to characterise the mixed nature and composition of the pixels (see *Field measurements and validation*).

Traditionally, image classification used statistical procedures on the assumption that pixels were composed of pure materials. Pixels were ‘binned’ into categories or classes of land-cover to represent the spatial distribution of these materials. Subpixel spectral un-mixing (see *What do the data show?*) has improved on these procedures (e.g. Goetz et al. 1985; Kruse 1999). The method disaggregates each pixel’s characteristic spectral signature into a set of possible pure signatures, provided these are available from a spectral library. For vegetation, some spectral libraries contain reflectances for both sunlit and shaded leaf, wood and litter materials for key species. See additional details in Aspinall et al. (2002).

Future prospects

Imaging spectroscopy (or hyperspectral remote sensing) is advancing apace because of its potential for accurately and quantitatively characterising materials, the recent launch of hyperspectral satellites and increases in computing power. Most remote sensing courses in universities now have specialised units in imaging spectroscopy or simply include it in the general remote sensing courses. To be effective, practitioners need good computer skills and geographical knowledge – ideally they also need strong numeracy and an optics or physics background to understand the details of the theory of optical radiative transfer. Most land resource survey agencies employ or subcontract such specialists.

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Temporal analysis with remote sensing

NC Coops, TR McVicar

Introduction

Remote sensing can provide series of measurements of the Earth's surface in time. Since the operational use of aerial photography from the 1930s and the launch of the first satellites for remote sensing in the 1960s, large archives have accumulated that can be used to reveal the changing structure, function and composition of terrestrial ecosystems. The data in these archives, once correctly geo-registered and radiometrically calibrated, can provide land managers with a wealth of information on land cover and land use.

Time-series data from remote sensing can be used to detect change at varying grain in both space and time. For example, the National Oceanographic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR) has been operating since 1978 and it provides frequent imagery (typically two overpasses per day per satellite over the same location) at low spatial resolution (1.1 km at nadir extending to 5.6 km at the edge of the swath). The current constellation of NOAA satellites can obtain up to six images of the same location per 24-hour period at a variety of acquisition times and viewing angles. By contrast, the Landsat Multi-Spectral Scanner (MSS) (80 m spatial resolution, first launched in 1972) and Thematic Mapper (TM) (30 m spatial resolution, first launched in 1982) provide finer spatial resolution but have a repeat cycle only every 16–18 days. The period between consecutive cloud-free images may be longer than 16 days in cloudy regions. Air photographs generally have a fine spatial resolution but are infrequent in time. Such photography is obtained typically at sampling intervals ranging from years to decades.

If the land surface feature to be monitored provides a detectable spectral response, the first step in using multi-temporal remote sensing data is to match the temporal density and spatial resolution of the imagery to the temporal variations in the land surface phenomena of interest. This is critical. Detection of broad-scale variations over time is likely to be spurious unless fine variations are explicitly accounted for (Lambin 1996). For example, if data are available only twice per year, one will be unable to assess the variation within years. This limiting frequency is called the Nyquist frequency and is well known in time-series analysis. Daily, diurnal or more frequent imagery is best suited to monitoring changes on short time scales (e.g. with respect to land-surface temperature, moisture availability, fire spread). Weekly (7–10-day) imagery is better suited to monitoring crop growth, and annual imagery is best for detecting variation in forest growth and land clearing (Table 12.1).

Temporal remote sensing is often used to detect change in land cover and vegetation (see *Chapters 8 and 9*). Running et al. (1994a) employed temporal analysis of remote sensing data to develop a method for global classification of land cover after finding that, because of spectral misclassification, single images could not provide sufficient information to classify land cover.

Table 12.1 Typical applications for temporal remote sensing in land evaluation and suitable time series

Application	Temporal scale	Sensor	Sensor repeat cycle
Land surface temperature	Daily	AVHRR	2 per day
Agricultural crop growth	Weekly to growing seasons		
Soil moisture modelling	Daily to weekly		
Fire disturbance	Daily to monthly	Landsat TM	16 days
Forest growth	Annual		
Woody weed encroachment	5–10 years	Landsat MSS ^A	18 days
Land use change	10–20 years	Landsat MSS and aerial photography	18 days to 1–5 years

^A The repeat cycle of Landsat 1, 2 and 3 was 18 days, whereas Landsat 4, 5 and 7 was 16 days. There is no MSS sensor on Landsat 7.

Temporal analysis with remote sensing has much to offer in the assessment of land resources. For example, analysis of repeated observations can provide insights into the structure, composition and phenology of the vegetation canopy. It can be used to determine the permanence of the living biomass above the ground (crops, grasses, forest), leaf longevity (perennial, annual), and leaf type (evergreen, deciduous). It can also be used to estimate growth rates and land use change. These variations in vegetation provide sensitive measures of soil conditions, particularly nutrient status and the soil–water regime.

Selection and calibration of imagery for temporal analysis

When undertaking temporal analysis with remote sensing, the following factors need to be considered. Temporal analysis is sensible only if changes in the phenomena of interest cause detectable changes in radiance, emittance or backscatter (Smits and Annoni 2000). In addition this change in signal needs to be attributable to a real change at the land surface, rather than a change in non-surface factors such as atmospheric conditions, imaging and viewing conditions or sensor degradation (Hame 1988). Finally, the geometric matching of two or more scenes needs to be accurate, because small registration errors in images can have a large influence on results (Smits and Annoni 2000).

Radiometric correction

Success in analysis requires correctly deriving the true (not apparent) change in radiometric response over time. Due to scattering and absorption by gas and aerosols (Song et al. 2001), the atmosphere has a significant effect in many portions of the electromagnetic spectrum on the signal sensed by sensors on satellites or aircraft. Correcting imagery for the effect of the atmosphere can be absolute, where the sensor signal is converted to a surface reflectance, or relative, where the same value in a series of corrected images is assumed to represent the same reflectance irrespective of the true ground spectra (Song et al. 2001). Relative radiometric normalisation is appropriate for many monitoring applications. Several variations on this technique exist, but all require a set of reference sites that appear over the entire sequence of images. These sites (also known as pseudo-invariant features or PIFs) are generally

well-defined spatial objects in the scene that are interpreted as spectrally homogenous and stable (Furby and Campbell 2001). Light and dark features are required, and examples include lakes, mature forest of an even age, beaches and roads. Regression equations are derived over all spectral channels to ensure these spectral features remain consistent in a sequence of images (Yang and Lo 2000).

More complex, physically based techniques for atmospheric correction are available. These use atmospheric conditions at the time of overpass (e.g. content of water vapour, optical thickness of aerosols) to correct the imagery using the theory of radiative transfer. A limitation of these methods is the need for detailed observations of the atmosphere at the time of overpass – and that data are rarely available at the required locations. This limitation is even greater for retrospective analyses.

The surface reflectance detected by sensors with a large field of view (e.g. NOAA AVHRR and air photography) depends strongly on the geometric relationships between the sun, the target and the sensor. Different orbits or aircraft flight-lines over the same area, combined with changing viewing directions and positions of the sun, can create spectral differences unrelated to surface change. This effect of viewing geometry is known as the bidirectional reflectance distribution function (BRDF) (Liang and Strahler 2000). There are two broad approaches to minimising the BRDF effect on imagery. Empirical or semi-empirical functions have been proposed to remove, or at least minimise, the effect from imagery acquired with a wide-scanning angles or lenses, such as air photography, airborne videography, or wide-angle airborne scanner data (Richardson et al. 1992; King 1995; Pickup et al. 1995) or AVHRR and MODIS satellite imagery (Liang and Strahler 2000). Alternatively, if no atmospheric correction or BRDF normalisations are made, time-series imagery should be analysed only if it was obtained under similar viewing geometries.

Imagery obtained from narrow field-of-view sensors (e.g. Landsat MSS or TM, SPOT high resolution and some airborne sensors) do not have the same degree of distortion caused by the view angle. Nevertheless, time-series imagery is still affected by differences in illumination or sun angle. For example, imagery collected during June in the Southern Hemisphere will have less reflectance and more shadowing from topography and vegetation (caused by the lower sun angles) than imagery obtained in January when the sun is higher. As a result, the analysis of a time-series or detection of change is often undertaken on anniversary dates (annual cycles) or windows where viewing conditions and the sun's angle are similar (Coppin and Bauer 1996). In Australia, especially in the rangelands, annual variation in rainfall also introduces significant variation that can complicate interpretations relating to annual cycles.

The BRDF algorithms are being researched because of the availability of archives with consistent images from AVHRR and MODIS. In the future, data providers rather than users will most likely provide corrections to images using pre-processing algorithms.

Geo-registration

Poor geometric registration of images can be a significant source of error. Minimising this error is time consuming (Dai and Khorram 1998). Poor registration is caused commonly by geometric distortions that occur between images even when they have been acquired with the same sensor. These distortions are due to variations in aircraft or satellite altitude and velocity, effects of Earth curvature, and relief displacement. Some of these distortions are easily accounted for while the imagery is being acquired, but others, such as relief displacement and aircraft or satellite movement, require the use of ground control points and the matching of pixel-line locations to geographical coordinates. Registration between images should be less than 20% to 50% of the pixel dimension otherwise significant errors affect the detection of change (Dai and Khorram 1998; Igbokwe 1999).

Methods for temporal analysis

Many algorithms for detecting change have been developed during the last 20 years (e.g. reviews by Nelson 1983; Milne 1988; Singh 1989; Coppin and Bauer 1996). The most common approach in Australia has been to compare sets of independently produced classifications or transformations of imagery, or both, obtained on different dates. To do this, each image, once correctly pre-processed, is either independently classified or transformed in some way to produce a coherent result at each time step. These image sets are then processed on a pixel-by-pixel basis to determine the amount of (areal) change in the image. A change-detection matrix is then produced (Coppin and Bauer 1989). Numerical classification can be used to produce an independent set of land use classes. Image transformation is an alternative and it involves computing an index (e.g. for greenness) from each image and comparing index values through time. This approach is often used to assess land clearing or land use change. Important examples include the Bureau of Resource Sciences (BRS) analysis of land cover change (1990–95) in agricultural areas using Landsat TM data (Barson et al. 2000), forest clearing in Victoria from 1972 to 1987 (Woodgate and Black 1988), and the Statewide Landcover and Trees Study (SLATS) in Queensland (Danaher et al. 1998). The latter used remotely sensed data sets to assess clearing rates of woody vegetation. The Australian Greenhouse Office (AGO) has embarked on a continental assessment of vegetative cover change using multiple images from 1980 onwards (Furby 2001).

In these projects, vegetation cover at each time step is assessed by indices that discriminate between vegetated and non-vegetated cover. These indices can be based on one of: the raw values of radiance of pixels from selected spectral bands; relative radiance of combinations of bands (e.g. NDVI see *Chapter 11*); or statistical functions such as brightness, greenness or wetness transformations (Campbell 1984; Crist 1985; Campbell and Furby 1994). A set of thresholds is used to monitor the locus of the index through time, and outputs from the analysis show the cover of vegetation at each instant. Figure 12.1 illustrates the technique with

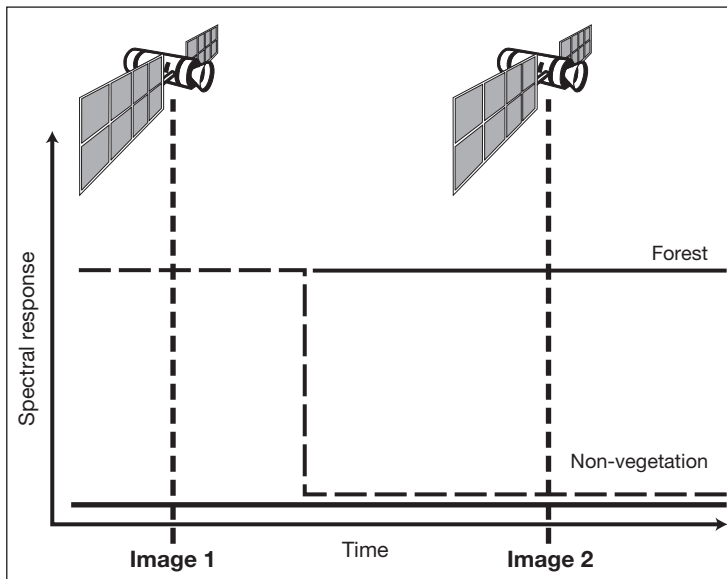


Figure 12.1 Detecting change in images collected on different dates. Between dates, areas of forest and non-vegetation have similar spectra; however, vegetation present in Image 1 and not in Image 2 can be classified as ‘changed’.

two images taken at different times. Areas of forest and non-vegetation have similar spectral responses between dates, but vegetation present in Image 1 and not present in Image 2 can be classified as 'changed'.

AVHRR archives contain frequent imagery in time but with coarse spatial resolution (Agbu and James 1994; Prince and Goward 1996). The imagery can be used to analyse regional-scale to global-scale phenology (Malingreau 1986; DeFries et al. 1995; Jakubauskas et al. 2001). Seasonal changes in greenness (e.g. NDVI) capture variations in phenology, and these can be quantified by measures of similarity (Coops and Walker 1996), Fourier analysis (Andres et al. 1994), wavelets (Meyer 1990) and harmonic analysis (Jakubauskas et al. 2001). Bennett (1979) provides a mathematical overview. In each technique, emphasis is both on temporal change and its spatial pattern, for example, the height, magnitude, duration and area under the time-series curve (e.g. Coops et al. 1999).

Notable Australian examples include the monitoring and assessment of vegetation growth and condition in grassland: Filet et al. (1990) developed predictions based on regression between maximum NDVI composites taken at 7-day intervals and the biomass of green grass. Likewise, Hobbs (1990) used the maximum NDVI to predict herbage biomass in central Australia for a complete growing season. Paltridge and Barber (1988) used NDVI imagery from AVHRR to monitor the status of surface moisture in grasslands using a Grassland Curing Index (GCI). Tucker et al. (1985) and Tucker and Sellers (1986) showed that AVHRR data integrated over time were related to the production of total dry matter and demonstrated the seasonal dynamics of vegetation globally (Justice et al. 1985). Figure 12.2 illustrates the technique with several images obtained during a single growing season. Eucalypt vegetation, by contrast, remains relatively constant throughout the year. The results allow the greening and senescing of crops to be monitored.

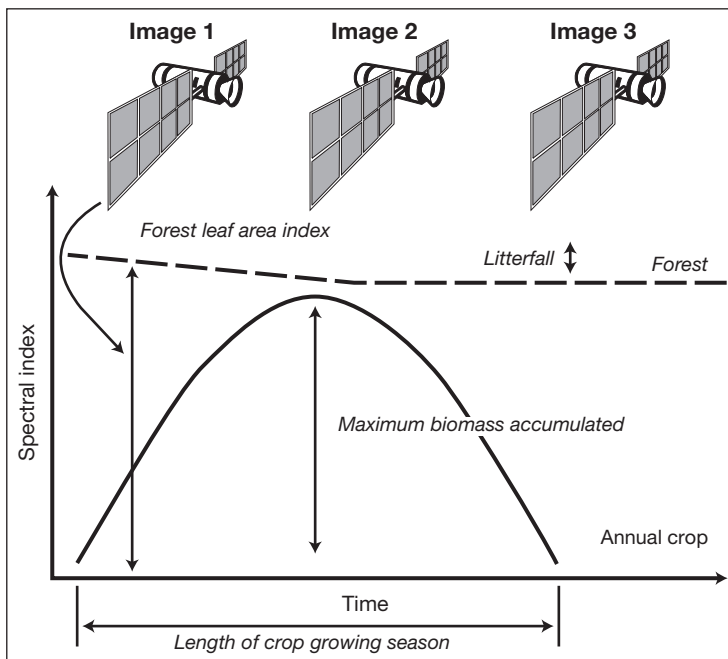


Figure 12.2 Detecting changes in parameters such as forest leaf area index, litterfall and rates of biomass accumulation using multiple images in a single growing season.

Useful attributes that can be extracted from temporal analysis of spectral indices include the length of growing season, rates of biomass accumulation, and, in forest, rates of litter fall and leaf area index (LAI). In woodlands, information can be obtained on the availability of resources, most commonly water, as the grassy understorey rapidly changes to exploit those resources (Roderick et al. 1999; Lu et al. 2002).

Models can also integrate observations from remote sensing with other spatial data sets relating to terrain and climate. The models range from semi-empirical to physically based models of processes. They usually couple ecological, hydrological and physiological submodels to estimate components of carbon, water and nutrient exchange across a broad array of landscapes. Data from remote sensing at a regional scale are ideal for such models in near real-time, provided the imagery can be linked to ground-based observations (McVicar and Jupp 1999). McVicar and Jupp (2002) used a resistance energy-balance model (REBM) together with estimates of day-time temperatures of the land surface derived from AVHRR. These were used to predict moisture availability across the Murray–Darling Basin of southeast Australia. The method successfully mapped regional moisture availability under annual crops, woodlands, forests and rangelands without relying on daily interpolation of rainfall. The approach can be integrated over longer times, and the annual difference (or anomaly) from the long-term mean has been compared to drought-declaration data provided by state agricultural agencies (McVicar and Jupp 2002). This comparison showed the utility of remotely sensed measurements in areas with sparse meteorological stations (McVicar and Jupp 1998). These methods have considerable potential for spatial prediction of soil properties, especially those driving the water balance.

Across forest, changes in greenness detected by satellites can be linked to variations in the LAI (Prince and Goward 1996). Hyperspectral sensors provide further information on concentrations of foliar nitrogen (Matson et al. 1994). These data are used either to set boundary conditions or to initiate parameters for ecosystem models. The FOREST-BGC model (Running 1994) uses estimates of LAI, derived from data at a monthly interval, to initialise site potential and predict forest production. The models GLO-PEM, GLO-PEM 2 (Prince and Goward 1996) and 3-PGS (Coops et al. 1998) are examples of models that predict patterns of biomass production using a combination of fine-grain spatial observations with a coarse time step (e.g. Landsat TM) and coarse-grain spatial observations that are frequent (e.g. AVHRR). These are used to predict variations in function or growth of the canopy.

The future

Temporal remote sensing advanced significantly with the MODIS instrument, which was launched on the EOS Terra platform in 1999. MODIS has a wide spectral range and a moderate spatial resolution (250–1000 m) combined with near-daily coverage of the complete Earth. A second MODIS was launched on the Aqua platform in 2002. It provides information on global radiation, surface reflectance, emissivity, snow and ice cover, and several vegetation indices (Running et al. 1994b). Data from MODIS are usually available within three hours of acquisition. Extensive field campaigns have been established to relate these remotely sensed measurements to studies on small plots. The latter have characterised ground and aerial fluxes from eddy covariance and atmospheric trace gases (Running et al. 1999).

Conclusion

The large capacity of airborne and spaceborne sensors to collect data should enable continuous monitoring of Australia's natural resources. However, the following needs to be observed:

- ensure the spectral signatures, frequency of acquisition and spatial resolution all match the phenomena being monitored
- once the imagery is obtained, calibrate it to ensure changes in signal are attributable to a true change at the land surface, rather than non-surface factors such as changing atmospheric conditions, imaging and viewing conditions, or degradation of the sensor
- ensure that geometric matching of a sequence of images is of high quality to avoid spurious results
- analyse time series and detect change using several approaches; the most common for land resource assessment involves comparative analysis of independently produced classifications or transformations of image data.

Finally, the increased use of GIS, coupled with developments in modelling of terrain and climate, have resulted in growing interest in integrating spectral time-series within physically based simulation models. These models are providing useful information at regional and continental scales on ecological, hydrological and physiological processes.

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Remote sensing with gamma-ray spectrometry

J Wilford

Gamma rays and data acquisition

Airborne gamma-ray spectrometry is a passive technique for remote sensing that measures the natural emission of gamma radiation from the upper 0.3–0.4 m of the land surface. Spontaneous radioactive decay caused by certain unstable isotopes in rocks and soil produces alpha, beta and gamma radiation. Alpha and beta radiation are particles whereas gamma rays are pure electromagnetic radiation with no mass or electronic charge. Gamma radiation has a frequency exceeding 10^{19} Hz and, unlike alpha and beta particles, it can travel through several hundred metres of air before it is effectively attenuated. These properties enable gamma emissions to be measured by ground-based or aircraft-mounted detectors.

Radioactive decay series and the gamma-ray spectrum

The principal gamma-emitting isotopes and their associated daughter isotopes used in geophysical surveys are ^{40}K (potassium), ^{232}Th (thorium) and ^{238}U (uranium). These can be used for estimating the amount of these elements at the surface. Potassium abundance is measured directly because gamma rays are emitted when ^{40}K decays to Argon 40 (^{40}Ar). Indirectly, U and Th abundances can be calculated by measuring gamma emission associated with their daughter radionuclides. The isotopes ^{238}U and ^{232}Th decay through 17 and 10 daughter isotopes, respectively, before reaching stable lead isotopes (Figure 13.1). Each of the intermediate daughter isotopes emits one or more of alpha, beta and gamma radiation, and each has a unique half-life. Since ^{238}U and ^{232}Th do not emit gamma rays, abundance is estimated from distinct emission peaks associated with ^{208}Tl (thallium) and ^{214}Bi (bismuth) in their decay chains. As a result, U and Th are expressed as equivalent eU and eTh.

Gamma-ray emissions, corresponding to ^{40}K , ^{208}Tl and ^{214}Bi , occur at distinct energy levels or peaks (Figure 13.2). Gamma-ray energies are measured in millions of electron volts (MeV), which are very small amounts of energy. Geophysical surveys record these isotopes by measuring gamma radiation in the following energy windows or channels: 1.37–1.57 MeV for K, 2.41–2.81 MeV for ^{208}Tl (used to estimate Th), and 1.66–1.86 MeV for ^{214}Bi (used to estimate U). The intensity of emission peaks for each radionuclide is used to determine the abundances of K, Th and U.

A fourth channel, called total count (usually used to estimate dose rate), is recorded between 0.4 and 3.0 MeV. The total count window measures a broad range of gamma-ray radiation from large to small energies compared with the more discrete windows for K, Th and U.

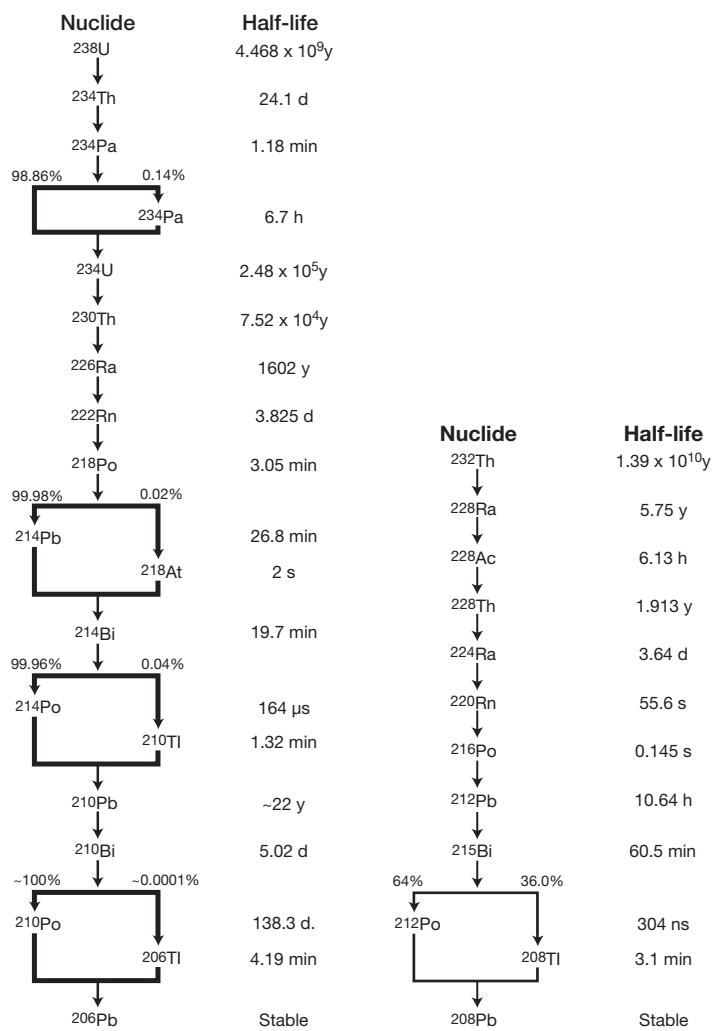


Figure 13.1 Decay series for Uranium 238 and Thorium 232 (after Minty 1997).

Radioelement equilibrium

The accuracy to which the daughter isotopes can be used to infer the abundance of Th and U depends largely on whether the decay chains are in equilibrium. Equilibrium in the decay series occurs when the individual daughter-products decay as quickly as they form. Disequilibrium occurs when one or more of the daughters in the series is preferentially increased, or removed, through processes such as precipitation, dissolution or diffusion. Disequilibrium is not a problem for sensing K and is usually not considered when estimating Th concentrations, but it can be a source of error in the determination of U concentrations. For example, radon gas (^{222}Rn) occurs above the short-lived ^{214}Bi in the U decay series (Figure 13.1). Release of radon gas through the soil or joints in bedrock and into the atmosphere can produce a marked effect on the activity of ^{214}Bi that is used to infer U abundance. Many soils in Australia have a slight U-rich disequilibrium as a result of gains or losses of U and its decay-chain daughter isotopes (Dickson 1995). Therefore, you need to consider disequilibrium effects when

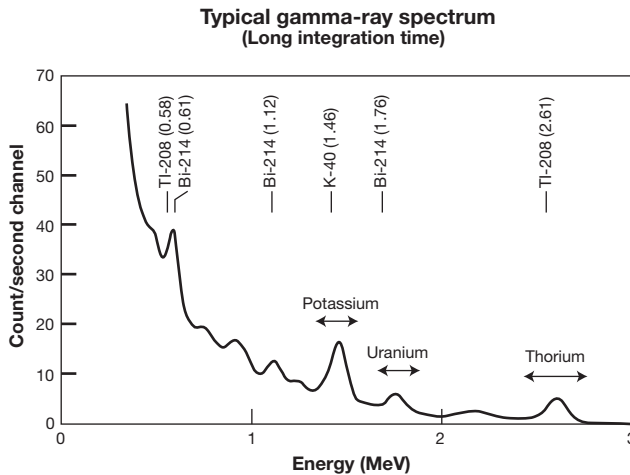


Figure 13.2 A natural gamma-ray spectrum with increasing frequency and energy levels (1 MeV = 10^6 electron volts). Prominent photopeaks, position of channel windows for K, Th, U and total count, and associated radioelements are shown.

evaluating U concentrations. Because of disequilibrium, radioelement concentrations are reported as equivalent uranium (eU) and equivalent thorium (eTh).

Data collection and resolution

Airborne gamma-ray data are collected from helicopters or aeroplanes at an altitude above ground of typically 40–100 m. Fixed-wing aircraft are used over flat to moderately hilly terrain, whereas helicopters are more effective over hilly terrain because they can maintain a consistent height above the ground. Sodium iodide scintillation crystals carried on board the aircraft detect gamma rays emanating from the land surface. A photomultiplier tube attached to the scintillation crystal records and amplifies the gamma-ray induced signal (Minty 1997).

The ‘footprint’ (or area sensed from the aircraft at a given instant) is a circle with a radius proportional to the flying height. For example, a survey flown at a flying height of 100 m would receive less than 40% of its signal from a circle with a 100 m radius (Figure 13.3). The resolution of airborne spectrometric data is improved by either flying lower, or using closer flight-line spacings, or both. Flight-line spacing is usually a compromise between data resolution and cost. Lowering the flying height reduces the size of the footprint and improves the raw data’s signal-to-noise ratio. However, in terms of spatial resolution, decreasing the flight-line spacing will provide a benefit to a point until the size of the footprint becomes a limiting factor. Much finer spatial resolutions are obtainable from ground surveys where hand-held or vehicle-mounted gamma spectrometers are linked to differential Global Positioning System (GPS) instruments. Selection of the optimum survey specifications (flight-line spacing, flying height, detector size) should be based on the scales at which soils change, and processes occur, within the landscape being investigated (Wilford and Minty 2006).

Measurements along each flight line are usually gridded into images with a pixel size typically one-fifth the flight-line spacing. For example, a survey line spacing of 400 m is interpolated to an 80 m pixel size. The large difference in ‘footprint’ (see *Chapter 3*) between ground and airborne measurements requires careful analysis when comparisons are made. As a guide,

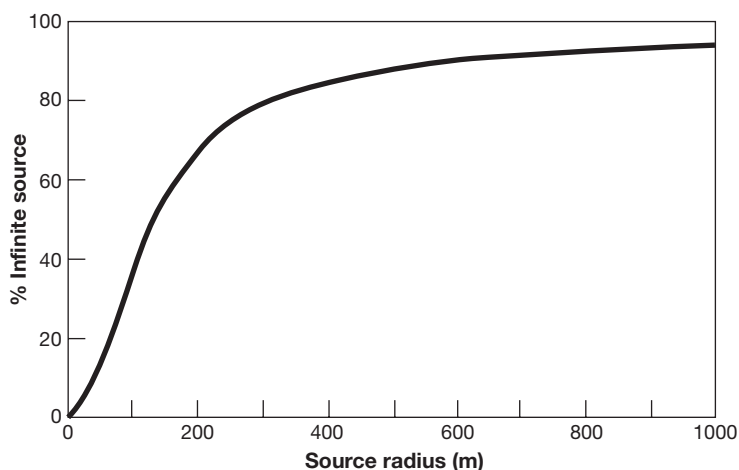


Figure 13.3 Percentage of the total signal originating from a circle with specified radius below the detector for thorium (Th) gamma-rays at 2.61 MeV and a detector height of 100 m (Minty 1997).

gamma-ray surveys flown with flight-line spacings of 400 m, 200 m, 100 m and 50 m have resolutions useful for mapping at respective cartographic scales of 1:250 000, 1:100 000, 1:50 000 and 1:25 000. Acquisition costs for airborne gamma-ray data are currently (2007) about A\$6.00 to A\$9.00 per line-kilometre. Thus, the cost to fly a 1:250 000 map sheet at 400-m line spacing is about A\$288 000 to A\$432 000. As a bonus, airborne magnetic-intensity data are usually collected at the same time as the gamma-ray data at minimal extra cost.

About two-thirds of Australia has gamma-ray spectrometric coverage. The quality of the data varies considerably, from very detailed surveys flown at low elevation and close line spacing (e.g. 40 m) to older regional surveys flown with a flight-line spacing of 1.5 km. Most have been undertaken by mining companies for mineral exploration and by government agencies for geological mapping. Increasingly, surveys have been flown in recent years for natural resource management (e.g. to support land resource survey and salinity investigations). Refer to Geoscience Australia (2006) for more information on airborne geophysical survey coverage and to Geoscience Australia (2004) to download airborne geophysical data.

Processing and noise removal

A range of factors can affect the shape and amplitude of airborne multi-channel gamma-ray spectra (Minty 1997). Accurate determination of radioelement concentrations in near-surface materials requires a series of processing steps including dead-time correction, energy calibration, aircraft and cosmic ray background correction, background correction for radon, striping, height correction, reduction to elemental concentrations and levelling (Table 13.1 and see Grasty 1976; Hansen 1992; Minty 1997).

The quality of data has improved as methods for removing noise from the raw gamma-ray signal have been refined. Further, the full 256-channel spectrum is now being exploited more effectively (Hovgaard 1997). The method uses principal component analysis of the gamma-ray spectra prior to the processing steps in Table 13.1. Refinements of the principal component technique (Minty and McFadden 1998) have led to further improvements in spectral purity. The results of these noise-removal techniques have meant improved image quality and increased accuracy of K, eTh and eU estimates.

Table 13.1 Steps in the processing of survey data from airborne gamma-ray spectrometry

Processing step	Description
Dead-time correlation	Corrects for potential loss in the total counting time available due to the time taken to process each individual pulse. The correction therefore multiplies the registered counts by a number that compensates for the time taken to record a pulse. This correction is usually minor but can be significant at high count rates.
Energy calibration	Corrects for energy drift in the spectra that result from changes in the gain of the photomultiplier tubes.
Aircraft and cosmic background correction	Corrections are made for radioactivity of the aircraft and its equipment, and from cosmic rays that interact with nuclei of the aircraft and detector.
Radon correction	Radon gas is mobile and its diffusion into the atmosphere can vary considerably in response to changing environmental conditions such as soil moisture, air pressure and temperature. The effects of radon gas can be significant (e.g. 50% of the counts in the U window can be associated with atmospheric radon gas and its daughter products). Two procedures can be used to remove background radon influences: – these are the spectral-ratio method and the use of upward-looking detectors (Minty 1997).
Stripping	A small proportion of photons in the Th window appear as counts in the lower energy U and K windows. The same occurs for the U window where some of the counts appear in the K window. The spectral overlap in the K, Th and U windows is known as Compton scattering. Corrections for Compton scattering involve the use of stripping ratios based on pure spectra. This is done using ground calibration pads with known radioelement concentrations.
Height correction	Corrections are made for the attenuation of gamma - rays resulting from the column of air between the ground and the aircraft. Most corrections apply an exponential attenuation of radiation as a function of flying height. However, in areas of high relief, more sophisticated algorithms are used.
Reduction to elemental concentrations	Count rates measured by the detector can vary between surveys because of the size of the crystal, detector efficiency and the widths of the windows. Count rates are converted into elemental abundances (as %K and ppm for Th and U) to enable comparisons between surveys and more useable estimates of radioelement abundances.
Levelling	Levelling involves removing changes along the flight -lines that result from changes in soil moisture, vegetation thickness and radon gas production during the acquisition phase of the survey. Crossover tie-lines are used to level the data. Levelling is principally used to remove noise in the U channel.

K, potassium; U, uranium; Th, thorium.

Image enhancement and display

Individual radioelement channels (i.e. K, Th, U and total count) are typically displayed as individual pseudocoloured images or combined as composite images. Three-band composite images are usually displayed with K in red, Th in green and U in blue (Figure 13.4, Plate 2, p. 420). Subtle variations in both image tone and texture show up when histograms of individual or composite bands are stretched or when ratios of bands (e.g. K/Th) are displayed. Linear stretching of histograms preserves spectral integrity and allows relative concentrations of K, eTh and eU to be directly correlated with the geochemistry of near-surface materials. Colour modulation techniques applied to composite images of the three bands can enhance colour variation (Milligan and Gunn 1997) by removal of dark and saturated areas.

Values for K, Th, U and total count are often expressed in counts per second. Calibration of the instruments against a known source of radioisotopes enables conversion from counts to percentage K and parts per million eU and eTh. These estimates assume equilibrium in their respective decay series.

Radioelement characteristics of rock and soil

Gamma rays emitted from the land surface relate to the mineralogy and geochemistry of the underlying materials (i.e. soil, regolith, substrate). Therefore, gamma-ray imagery can be viewed as a surface geochemical map that shows the distribution of the radionuclides K, Th and U. In erosional landscapes, bedrock responses are likely to dominate the image, whereas in depositional and weathered landscapes, responses associated with soil and regolith materials are likely to dominate. The latter usually have little relief and low rates of geomorphic activity.

Radionuclides in bedrock

Average crustal abundances of K, Th and U are, respectively, 2.35%, about 12 ppm and about 3 ppm (Dickson and Scott 1997). Fractionation of K, Th and U during rock formation generally increases with silica content; this shows up as a general trend towards increasing K, Th and U as igneous lithologies move from basic to acid (Figure 13.5, Table 13.2).

Potassium occurs in many rock-forming minerals including orthoclase and microcline feldspars, muscovite, alunite and sylvite. Potassium is most abundant in acid igneous rocks including granite, rhyolite, syenite, nepheline and pegmatite. Potassium is absent or at very small concentrations in mafic minerals and associated rocks such as basalts, dunites, serpentines and peridotites.

Uranium occurs in two main valence states: U^{4+} and U^{6+} . The oxidised U^{6+} forms complexes with oxygen to create a uranyl ion (UO_2^{2+}). Uranyl ions are mobile and typically form soluble complexes with the anions carbonate (CO_3^{2-}), sulfate (SO_4^{2-}) and phosphate (PO_4^{3-}) depending on the geochemical conditions (Langmuir 1978). In soils the mobility of U^{6+} is modified by adsorption to hydrous iron oxides, clay minerals and colloids (Dickson and Scott 1997). Under reducing conditions, the more reduced U^{4+} form is largely associated with insoluble minerals.

As with K, Th and U minerals precipitate late in the igneous crystallisation sequence (Galbraith and Saunders 1983). Uranium occurs in minerals such as uraninite, carnotite and gummite. Uranium is most common in rocks such as pegmatites, syenites, carbonatites and certain granites and black shales.

Thorium has a single valence (4+) in near-surface environments and so its mobility does not alter under changing redox conditions. Thorium solubility is generally low, although it can be dissolved in acid solutions or at neutral pH when associated with humic acids. Thorium occurs in minerals such as thorianite and thorite and rocks including granite, pegmatite and gneiss. Thorium and U are found in accessory and resistant minerals such as zircon, sphene, apatite,

Table 13.2 Abundances of radioactive elements of different rock types in Australia and associated soils derived from them

Rock type	Rock			Soil		
	K (%)	U (ppm)	Th (ppm)	K (%)	U (ppm)	Th (ppm)
Intrusives						
Granitoids	0.3–4.5 (2.4)	0.4–7.8 (3.3)	2.3–45 (16)	0.4–3.9 (2.1)	0.5–7.8 (2.7)	2–37 (13)
Gneissic rock	2.4–3.8 (2.4)	2.1–3.6 (2.5)	18–55 (15)	0.7–1.9 (1.3)	1.6–3.8 (2.2)	6–19 (12)
Pegmatite	2.6–5.5 (3.7)	0.3–1 (0.7)	0.3–9.6 (2)			
Aplites	0.6–4 (2.4)	1–8 (3.3)	3–20 (7)			
Quartz–feldspar porphyry	1–5 (2.9)	1.3–2.9 (1.7)	6–14 (13)			
Intermediate intrusives	0.7–5.6 (2.7)	0.1–1.2 (0.8)	0.8–6.1 (2.4)	0.7–3.4 (1.6)	1.5–2.3 (1.9)	2.9–8.4 (5.6)
Mafic intrusives	0.1–0.8 (0.4)	0.0–1.1 (0.3)	0.8–3.1 (1.2)			
Extrusives						
Felsic volcanics	2.0–4.4 (3.7)	1.4–13 (2.4)	13–28 (17)	1.8–3.2 (2.4)	1.3–2.4 (2.1)	10–18 (13)
Intermediate volcanics	1.8–4.1 (2.7)	0.9–5.6 (2.3)	1.5–15 (9)	1.0–2.7 (1.9)	1.2–3.6 (2.1)	4–17 (10)
Low-K andesites	0.7–0.9 (0.8)	1.0–2.5 (1.6)	3–8 (5)	0.8–1.5 (1.1)	1.2–1.5 (1.3)	4–6 (5)
Mafic volcanics	0.3–1.3 (0.9)	0.3–1.3 (0.7)	2.0–5.0 (3.0)	0.2–1.4 (0.7)	0.6–2.5 (1.6)	3.3–13 (7.9)
Ultramafic volcanics	0.2–0.9 (0.4)	0.3–0.9 (0.6)	0.0–4.0 (1.2)	0.6	2.0	6
Sedimentary rocks						
Archaean shales	0.4–1.6 (1.9)	0.3–1.3 (0.9)	1–5 (2.7)	0.8	1.2	3
Other shales	0.1–4.0 (2.6)	1.6–3.8 (2.6)	10–55 (19)	0.7–3.0 (1.5)	1.2–5 (2.3)	6–19 (13)
Arenites	0.0–5.5 (1.8)	0.7–5.1 (2.3)	4–22 (12)	0.1–2.4 (1.3)	1.2–4.4 (2.1)	7–18 (11)
Carbonates	0.0–0.5 (0.2)	0.4–2.9 (1.6)	0–2.9 (1.4)			

Average value in parentheses (from Dickson and Scott 1997.) (K, potassium; U, uranium; Th, thorium.)

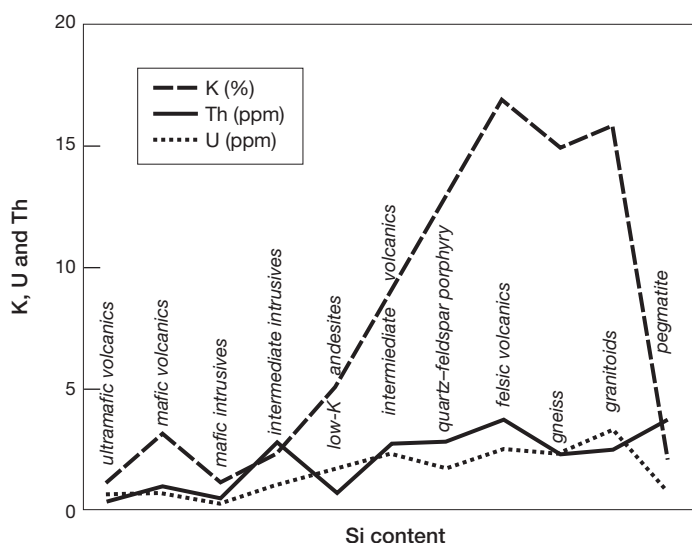


Figure 13.5 Variation in average potassium (K), uranium (U) and thorium (Th) content for igneous rocks with increasing acidity (Si content) (Dickson and Scott 1997).

allanite, xenotime, monazite and epidote. Zircon, the most common of these minerals, can accumulate in weathering profiles (Wilford et al. 1997; Fitzpatrick and Chittleborough 2002), placer deposits and in the heavy mineral fractions of clastic sediments (Hansen 1992). Uranium and Th can also occur in small quantities in major rock-forming minerals such as quartz and feldspar.

Behaviour of radionuclides during pedogenesis

During weathering, the distribution and relative concentration of these radioelements changes from the amounts present of the initial bedrock source (Table 13.2). Fortunately for soil mapping, K behaves very differently from Th and U during weathering and pedogenesis. In most cases, the concentration of K decreases with increased weathering. This arises because K is highly soluble and, given sufficient time, leaches from the profile. In landscapes with bedrock rich in K, variations in K concentration in the upper part of the weathering profile can be used to delineate highly leached soils and areas with rapid erosion (Wilford 1992). However, K can persist in soils where it is present as muscovite (K-mica) or where it is associated with large phenocrysts that take longer to weather (Dickson and Scott 1997). Potassium is also associated indirectly with clays such as illite where it is absorbed on the surface in small amounts. In contrast, U and Th are associated with relatively stable constituents in the soil profile (Figure 13.6). Uranium and Th released during weathering are readily absorbed by clay minerals, oxides (iron, Fe; aluminium, Al) and organic matter. Large concentrations of U and Th can also be associated with resistant minerals such as zircon and monazite – these are often preferentially concentrated in highly weathered landscapes. Uranium is leached from soluble minerals under oxidising conditions and precipitates in reducing conditions. Large concentrations can be associated with radium-226 exsolved from groundwater (Giblin and Dickson 1983; Dickson 1985) or radon gas in soils (Grasty 1994).

Gamma-ray response in erosional landscapes and relationships with geomorphic processes

Gamma-ray signals from erosional landscapes broadly correlate with bedrock geology. However, variation within a major lithological group depends on the overlying soil and regolith

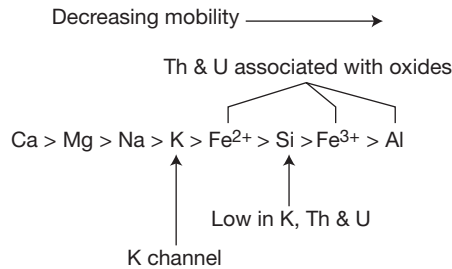


Figure 13.6 Relative mobility of major mineral constituents released during weathering and their associated gamma-ray responses. Potassium is typically lost early during bedrock weathering: low K, Th and U can be used to map siliceous soils; and elevated Th and U can locate highly ferruginous and aluminous soils.

materials, so that for a given bedrock type, the gamma-ray response will reflect the balance between erosion and soil production (Figure 13.7). Quickly eroding zones are likely to have thin soils and gamma-ray responses that are close to those of the bedrock in terms of geochemistry and mineralogy. However, landscapes with stable surfaces that are less active will preserve weathered materials and the gamma-ray responses will respond accordingly. In this way, images from gamma-ray spectrometry can be used to separate zones of contrasting geomorphic activity (see Wilford 1995; Wilford et al. 1997; Pickup and Marks 2000).

Dickson and Scott (1997) studied radioelement trends in soil profiles formed *in situ* on several types of bedrock. Soil developed on granitic rocks had a radioelement signature reflecting the mineralogy of the bedrock and its weathering. About 20% of the radioelement content was lost through pedogenesis. Losses of K were related principally to weathering of K-feldspars, although Dickson points out that, during the early stages of weathering, the K content can increase as result of the preferential removal of more soluble mafic minerals. Uranium and Th concentrations in the soil were more varied. Soils developed on felsic bedrock types had lost K, U and Th. Soils on mafic volcanic rocks (e.g. basalts) were depleted in K but had gained U and Th as a result of their association with iron oxides in the soil profile. Similar gamma-ray patterns have been found on shaly rocks but soils developed on quartz-rich sandstones have generally small concentrations of radioelements which barely differ from those of the underlying bedrock.

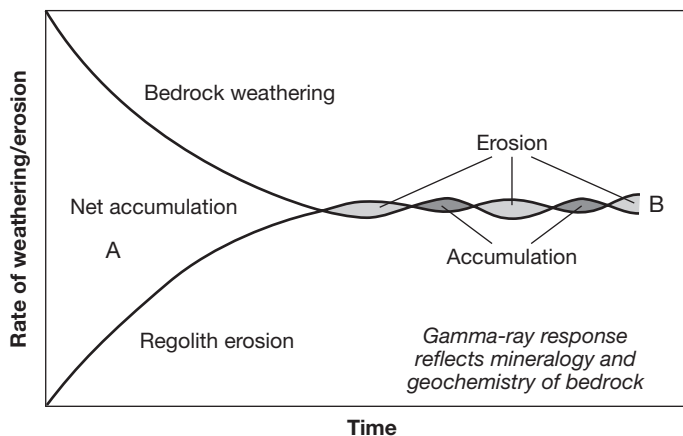


Figure 13.7 Relationship between gamma-ray response and denudation balance in landscapes. (a) Areas of active erosion where the gamma-ray response will reflect bedrock geochemistry and mineralogy. (b) Areas where the rates of weathering are higher than the erosion rates the gamma-ray response will reflect regolith and soil geochemistry and mineralogy (Wilford et al. 1997).

Gamma-ray responses in depositional landscapes

Responses of sediments reflect the geochemistry and mineralogy of their sources, subsequent weathering and degree of sorting (e.g. Pickup and Marks 2000). The gamma-ray signal from young sediments will indicate the geochemistry of their source. Weathering will modify the gamma-ray activity, so that gamma-ray imagery can be used to assess the relative depositional activity of fluvial systems (Wilford et al. 1997; Pickup and Marks 2000). Different responses can also be caused by particle size controlled by sorting of sediments during deposition (e.g. fine sediments from over-bank flows versus sandy bed-load deposits). Separating the effects of sorting and weathering in the gamma-ray response will nearly always require field investigation. Likewise, stratigraphic investigations are needed to separate the gamma-ray responses of windborne sediments from alluvium – in landscapes of low-relief gamma-ray imagery can be invaluable for this purpose (e.g. McKenzie and Gallant 2006).

Sandy aeolian materials usually have low concentrations of the radioelements, appearing black in ternary radiometric images. In contrast, finer textured materials such as parna (Butler 1956) exhibit moderately large values for Th. Parna is widespread, covering large areas of the Western Plains, Riverina and parts of the tablelands of New South Wales. In the Blayney district, Dickson and Scott (1998) recognised soils with a significant aeolian component by their elevated Th content (11 ppm eTh) compared with that of the underlying bedrock. They also recognised that similar radioelement patterns could be generated by other pedogenic processes. Parna does not appear to have a unique signature – different kinds of rock and sediment and patterns of pedogenesis produce similar radioelement associations.

Intensely weathered and indurated materials

Modifications in radioelement concentration caused by weathering are most obvious in intensely weathered materials and associated duricrusts. For example, strongly leached aluminous and ferruginous bauxitic soils in the Weipa region have small values of K and large values for eTh and eU (Wilford 1992). This reflects the very small cation exchange capacity and large concentrations of iron and aluminium oxides and resistate minerals (e.g. zircon). Similar radioelement trends are evident in intensely weathered granites, where most of the K has been lost and U and Th have been retained because of their association with resistate minerals, oxides and clays (Dickson and Scott 1997).

Ratios of airborne gamma-ray K and Th have been used to discriminate regolith materials from bedrock signatures in the Yilgarn Craton of Western Australia (Dauth 1997). Dauth (1997) showed that small K/Th ratios are related to strongly weathered and ferruginous saprolite. Ferricrete gravels in Western Australia can show small concentrations of K as a result of intense weathering and large concentrations of Th as a result of scavenging by iron oxides (Cook et al. 1996). Wilford et al. (1998) used the large Th values in the Gawler area of South Australia to separate ferruginous lags and granules in sandy soils from uniform-textured gradational sands. Deep, sandy, strongly leached and moderately acid soil profiles over granitic rocks in Cape York Peninsula were identified by their small K, Th and U response (Biggs and Philip 1995). Similarly, sandy soils derived from strongly weathered bedrock materials were delineated by their very low radioelement counts, reflecting the abundance of quartz at the surface (Cook et al. 1996). Silcretes in Western Australia were identified by their small K and relatively large Th and U values. Large Th and U may relate to resistant minerals in the silcrete or contamination of Th-rich and U-rich ground water during silicification, or both (Wilford et al. 1997). Calcretes have generally small concentrations of radioelements although calcretes can, in places, pick up subtle radioelement patterns traceable back to the bedrock that they cover (Dickson and Scott 1997).

Effect of vegetation on gamma-ray response

Most gamma rays pass through vegetation but a dense cover can attenuate the signal. Aspin and Bierwirth (1997) detected a signal loss of between 11% and 22% in gamma rays above mature pine plantations. Reflectance imagery capable of estimating above-ground biomass may be useful for identifying where attenuation effects are likely. Lavreau and Fernandez-Alonso (1991) provide an example in an equatorial landscape with a thick cover of forest.

It is helpful to consider translocations and transformations within soil profiles when interpreting gamma-ray imagery. Martz and de Jong (1990) noted that differences in isotope concentrations between the A and B horizons were due partly to the degree to which different isotopes were cycled by plants. Although ^{40}K is more susceptible to leaching, its concentration was largest near the surface. This is probably as a result of selective uptake of ^{40}K by plants and incorporation in the surface horizon via through-flow, stem-flow, litter-fall, root decomposition and bioturbation. The distributions of some radioelements can be related to processes induced by vegetation and bacteria (e.g. Pate et al. 2001, Verboom and Pate 2006).

Applications in land resource survey

Gamma-ray spectrometry, together with other geophysical data and satellite imagery, are now used routinely in land resource surveys. Although gamma-ray spectrometry was initially developed for the mining industry (notably U exploration), since 1990 there has been a rapid increase in its use for soil and regolith mapping. It has also become valuable for catchment planning (George and Woodgate 2002; Pracilio et al. 2003).

Data from gamma-ray spectrometry are invaluable for land resource surveys because they can be used to good effect in several ways.

- Qualitative interpretation of images depicting one or more elements provides a good basis for gaining a better understanding of landscape variation and likely processes. The imagery can be used as input to qualitative survey (see *Chapter 19*).
- Radioelement data, when draped over digital elevation models with shaded relief, provide a three-dimensional perspective difficult to attain using other methods. Dynamic viewing of digital landscapes has opened new ways of examining land resource data that are yet to be fully exploited.

Radioelement data can be classified into groups with similar spectra. Following ground validation, the classes can then be assigned soil attributes. Classification can produce simplified maps for interpretation or thematic soil maps in which major radioelement associations are linked to observations on soil. However, different soils can give similar gamma-ray signals and this can be difficult to detect. In addition, during classification subtle gamma-ray and textural features are, to some extent, typically lost.

- Finally, radioelement data can be used directly as a predictor for digital soil mapping. Australian examples include Gessler et al. (1994), Bierwirth (1996), Cook et al. (1996), McKenzie and Ryan (1999), Corner et al. (2002), Taylor et al. (2002), Pracilio et al. (2003), McKenzie and Gallant (2006) and Wilford and Minty (2006).

Gamma-ray spectrometry has been rapidly adopted in land resource survey because it is the best method for remote sensing that characterises soil and substrate materials. It has many advantages over reflectance-based methods that sense only the upper boundary of land cover. The gamma-ray signal is integrated over a volume of material, with >90% of gamma rays emanating from the upper 0.5 m of a dry profile (Gregory and Horwood 1961).

Limitations and future directions

The same radioelement signal can derive from more than one material. Furthermore, relationships found in one region may not translate to another because of differences in weathering and bedrock. Therefore, as with other remote sensing techniques, gamma-ray spectrometry requires ground validation before the attributes of the soil or regolith can be confidently inferred.

The spatial resolution of airborne gamma-ray spectrometry is not as fine as other multi-spectral methods. Its large 'footprint' will smooth out local variation. High-resolution airborne surveys and, in particular, ground-based surveys, give more detail. For this reason, ground-based surveys are likely to play an increasingly important role in soil mapping, particularly to support precision agriculture.

We are still at an early stage in understanding the distribution of radioelements in soil and regolith, how radioelement abundances are modified during pedogenesis, and the linkages between variations in radioelements and geomorphic processes. As our knowledge improves, so will our ability to infer the properties of the soil and regolith and the understanding of landscape processes will increase likewise.

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Part 3

Survey mechanics

The practicalities of undertaking land resource survey are described. Survey specification and planning is the most important step because most subsequent decision on resources, sampling, measurement and survey method depend on it. These stages are considered before describing field operations and qualitative survey.

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Survey specification and planning

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Introduction

Success of any survey depends on proper specification and sound planning. It involves reiteration between the client and the project manager to achieve the best possible outcome with the given finance, staff, and physical resources. Time spent on answering the questions *why, what, when, how, who* and *how much* is returned many times over, with surveys completed on time, within budget and to the client's requirements.

Specification sets the rules for the project and defines the expected outcomes. It states *why* the project is required and *what* needs to be done (e.g. a combined mapping and monitoring program). It also states *how* the project is to be done (i.e. the technical specifications); it may specify *who* does the work, thereby ensuring project staff have appropriate qualifications and experience; *when* the work is done and date of completion; and *how much* it will cost. Specifications are developed through negotiation between the client and project manager before work commences. They are usually specified in the Terms of Reference.

Planning concerns the mechanics of making the project work. It sets the framework for the project to meet the project specifications. It includes managing resources of people and money for the task. This involves the *who, how* and *when* of the project. At the tactical level it deals with day-to-day running of the survey.

The Terms of Reference form the backbone of the specification and planning process. Complete this document first. The Terms of Reference establish agreed conditions between the client and the provider. It sets a framework for the project manager to conduct the survey. The Terms of Reference protect both the client and the provider from unnecessary disputes and usually have the following structure:

1. Contents
2. Background
3. Objectives and purpose
4. Scope and technical specifications
5. Resources
6. Project management
7. Constraints and assumptions
8. Outputs
9. Financial and legal obligations
10. Supporting documentation.

The degree of detail in the Terms of Reference corresponds to the size and complexity of the project. A simple one-day survey requires only a brief statement on agreed outputs, whereas

a major international project lasting several years may have detailed and legally binding terms of reference with financially punitive clauses for non-compliance.

This chapter examines each category in the Terms of Reference. Use this chapter as a checklist when specifying and planning a project. There are several excellent guides to project planning and management. A standard reference is PMBOK (Project Management Institute 2000) – this publication has also been designated as an American National Standard (ANSI/PMI 99-001-2000). The guidelines in AusAID (2005) for implementing the ‘*Logical framework approach*’ are also highly recommended.

Background to the survey

Define the location and extent of the project, along with a justification that includes benefits, and an assessment of the impact of not proceeding. Identify existing relevant work (e.g. surveys, unpublished data, anecdotal evidence).

Objectives and purpose of the survey

The rationale for nearly all surveys is to aid planning and management in some way. Surveys provide information on what soil or land resources are in a region, where they are located and what they can be used for. Chapter 1 emphasised that the key test of utility for a survey is *whether the new information reduces risks in decision-making*. A change in land management, if it occurs, arises as a result of the information reducing the uncertainty about impacts of different strategies (Pannell and Glenn 2000). A wide range of biophysical, economic and social factors contribute to uncertainty – it is necessary to identify these factors because they will influence the ultimate value of the survey. A few investigations have a purely scientific rationale (e.g. to improve understanding of biophysical processes and landscape evolution) and success in these cases is measured on less utilitarian grounds (e.g. testing of hypotheses and providing basic knowledge).

The first step in any survey or project is clear specification of purpose. The purpose needs to state why and for whom the survey is being undertaken as well as what the survey should achieve and how the achievements will be measured. These statements help to decide the method of survey and intensity of sampling or, indeed, if a survey is required at all. Most projects require outputs to be expressed as some form of land evaluation (e.g. land suitability for specific forms of land management). See *Chapters 27 and 28* for a detailed description of the options.

Identify the beneficiaries of the information – they might not be obvious, especially for general purpose surveys. In many cases (e.g. special-purpose surveys for agricultural development), the clients are the beneficiary and their needs are unambiguous. However, with public agencies, regional communities are likely to be the primary beneficiaries. As a result, proposed outcomes are often less distinct. General purpose surveys require at least one objective to address plans for longer term management of data generated by the project.

Objectives need to be in a form that satisfies the following criteria:

- *specific* – the desired outcomes are clearly stated
- *measurable* – it is feasible to determine whether each objective has been achieved at the end of the project
- *agreed* – objectives are agreed by all interested parties
- *realistic and achievable* – objectives are feasible within the time and resources available
- *time-bound* – it is clear when the objectives will be achieved; for most objectives this will be at the agreed finishing date for the project, but some may need to be achieved before the end.

Pilot study or needs analysis

It may be appropriate to undertake a pilot study or strategic needs analysis before a major survey is commissioned. A survey may not be required.

Benefit–cost analysis

Land resource assessments are investments in knowledge. Like any assessments, they involve initial costs, an expectation of benefits flowing from the use of the products, and some uncertainty. At its simplest, benefit–cost analysis poses the question of whether the benefits likely to flow from the investment can reasonably be expected to exceed the costs of the survey, or whether the resources could be otherwise deployed in a more valuable way.

Identify the expected benefits and costs before commissioning a project. The ratio of benefits to costs might be improved by modifying some factors of the design. ACIL (1996) demonstrated that general purpose land resource surveys have very large benefit-to-cost ratios. It also provides guidelines for, and examples of, benefit–cost analyses in land resource assessment. A benefit–cost study can be an important prelude to a major study – it can also assist in obtaining further funds. Another useful study is by Sanders (2003).

While benefit–cost analysis can be valuable, there are several methodological issues (e.g. unpriced values, choosing appropriate interest rates, identifying avoided costs). Slavish adherence to benefit–cost ratios may lead to unprofitable investment.

Multiclient survey

Identify the likely beneficiaries of a survey when the work is commissioned. Some of them may be recruited as additional clients. Doing so will have the dual benefit of tailoring the survey to meet the needs of as many clients as possible, and providing additional funds for the survey. These are especially relevant to publicly funded work. The likely *future* needs of the public should be considered in the survey specifications so that the long-term worth of the work is maximised.

Where the beneficiaries of the survey are not obvious, market research or survey of potential beneficiaries should determine who will benefit, and to what degree, so that the survey can be justified and properly targeted. Vision and foresight should pay dividends in the future.

Interdisciplinary teams

The benefits of a land resource survey will usually be improved if it is interdisciplinary. The benefits arise from interactions between team members. There is also greater work satisfaction and interest for the project team. The integrated surveys undertaken across large areas of Australia by CSIRO, and state and territory agencies, demonstrated the benefit of the approach (Christian and Stewart 1968; McKenzie 1991).

An interdisciplinary approach will often lead to economies of scale, especially for surveys in remote locations where the costs of getting a team to the area are substantial. An interdisciplinary team can share resources and keep costs down.

There may be logistic issues related to managing staff across projects being run in parallel. In these circumstances it will be necessary to use standard project management techniques such as Gantt or PERT (Program Evaluation and Review Technique) charts, and workflow diagrams to manage resources (see AusAID 2005). Maintaining the composition of an interdisciplinary team can be challenging.

Scope and technical specifications

Scope

Scope defines the geographical extent of the project, and may also include the technical specifications, inputs and outputs. It may also list the expected uses of the information outside the immediate terms of reference. This heading can be used to describe how the project builds on previous work and identify relations with other work.

Survey design and approach

Make sure the survey design will satisfy the desired outcomes. The clients, depending on their understanding of survey methods, may wish to have a role in determining the survey approach and how this influences the final outcome. It is more common for the client to be concerned with costs, time limits and outputs. One might have to modify the expected outcomes by limitations such as costs, availability of expert staff and logistics. The last factor can lead to adjustments in expected outcomes.

If you are commissioning the survey, then refer to *Chapter 2* prior to selecting a method. Benefits from a survey often accrue over considerable time. These long-term benefits need to be counted in a benefit–cost analysis. The Australian experience has been that sound studies can still generate substantial benefits more than 40 years after their completion (e.g. Gibbons and Downes 1964; Northcote et al. 1960–1968).

Two key areas for decisions relate to the breadth of purpose (general versus special), and collection of minimum data sets.

General purpose versus special purpose surveys

General purpose surveys are designed to provide information to one or more clients or stakeholders, often over a long time. They usually record a broad range of information that is considered to have both current and future use. This is efficient because the cost of revisiting sites can be substantial. The amount of additional data that should be recorded beyond the requirements of the commissioned survey is difficult to decide – the temptation is to collect more data than required. Sometimes the organisation doing the survey negotiates non-financial inputs to a survey to enable the collection of additional information as a trade-off for access to the data.

Special purpose surveys are generally smaller undertakings and are tailored to meet well-defined needs of clients. Examples of specific surveys include soil survey of farms to assess capabilities for particular crops, a single attribute survey such as the occurrence of wind erosion, and geotechnical investigations to map soils that shrink and swell and so damage pipes and cables. Data for specific surveys are usually targeted, and the collection of additional data is less common.

Minimum data sets

There have been many proposals for standard data sets to be collected in land resource surveys. Agreement on the ideal or optimum data set is rare, even within a small region with a limited set of land uses. However, it is fairly straightforward to reach consensus on a *minimum data set*. The advent of models for farming and hydrology has heightened the need for consistent sets of data to be available from sites across the country. The task of specifying minimum data sets for several purposes is made easier by recognising a hierarchy of scales in space and time. Minimum data sets are considered in *Chapter 17*. The key task for the individual person or organisation is to identify the appropriate level and type of minimum data set needed to satisfy different tasks.

Scale and resolution

Scale in land resource mapping has been referred to traditionally as cartographic scale (see *Chapter 3*). This relates the map to the field. For traditional maps, the scale of publication limits the size of the smallest area that can be legibly printed. As a general guide the minimum width of a feature on a printed map is between 1 mm and 2 mm. For a map published at 1:100 000 this equates to 100 m to 200 m on the ground.

It is important to determine and agree on the cartographic scale in the specification. Purpose guides the publication scale, and this in turn guides the intensity and type of information collected (Table 14.1). The agreed scale will strongly control the resources (in time and money) required to complete the survey, and this needs to be balanced with the client's needs and resources. As a general rule, survey effort is quadrupled for a doubling of cartographic scale (i.e. effort is proportional to map area).

Table 14.1 A general guide to map publication scale and its affect on the use of information (Moore and van Gool 1999, after McKenzie 1991 and Gunn et al. 1988)

Cartographic scale, survey intensity and approximate resolution ^A	Examples of recommended uses
> 1:10 000 Very-high intensity < 1 ha	• Detailed suitability for specific forms of land use • Intensive land use development (e.g. urban, horticulture, engineering uses) • Local urban structure planning • Detailed farm planning • Property development planning.
1:10 000–1:50 000 High intensity 1–25 ha	• General suitability for various forms of land use • Strategic planning for intensive land use developments including urban and horticulture • Shire planning for the development of rural land in shires experiencing high land use pressure (i.e. shires near the metropolitan region or major urban centre) • Management plans for small catchments • Farm planning for low intensity agricultural uses • Forestry production areas.
1:25 000–1:100 000 Medium intensity 6–100 ha	• General suitability for various forms of land use • Planning for low intensity land uses such as dry land agriculture • Strategic planning for more intensive land uses such as urban and horticulture • Shire planning for the development of rural land in shires experiencing moderate land use pressure (i.e. shires with larger rural towns that are experiencing some development pressure or have major development opportunities) • Regional planning in areas with high development pressure • Management of medium catchments • General planning of forests.
1:50 000–1:150 000 Medium to low intensity 25–225 ha	• Broad suitability for major kinds of land use • Best suited for planning low intensity land uses such as dryland agriculture • Generally locating more intensive land uses such as urban and horticulture • Regional and local planning for predominantly rural shires • Management of large catchment areas.

(Continued)

Table 14.1 (Continued)

Cartographic scale, survey intensity and approximate resolution ^A	Examples of recommended uses
1:100 000–1:250 000 Low intensity 100–625 ha	• Broad suitability for major kinds of land use • Strategic planning for broad dryland agricultural uses or for generally locating other major kinds of land use with limitations on the amount of detail that can be considered • Regional plans, planning for rural shires (particularly smaller wheatbelt and pastoral shires) • Overview of management issues for very large catchments • General planning for pastoral shires.
< 1:250 000 Reconnaissance > 625 ha	• Overview of land resources and their status • A general prediction of land resources in a given location • General planning for pastoral shires.
< 1:500 000 Overview > 2500 ha	• Overview of land resources and their status • General summaries of regional resources • National/regional resource inventory.

^A Resolution based on 1 cm² on the map. This figure is an indicator of the size of land use developments that can be planned for. Although the minimum resolution is assumed to be 0.5 cm² in Gunn et al. (1988), the average resolution of map units is usually much larger in practice.

Quantitative surveys require a different type of specification. It is preferable to agree on support, intensity of sampling and design. For environmental data and predicted soil attributes, specify the grain, extent, accuracy and precision of spatial position and the attributes of interest. Although spatial position has received considerable attention (e.g. Hunter and Lowell 2002), it is often difficult to specify the required accuracy and precision for soil attributes prior to field work.

Sampling scheme

The sampling scheme specified for the survey will be set by its purpose and by the mapping method specified (see *Chapters 18* and *20* for sampling options for land resource survey).

The minimum density of ground observations needs to be specified because this controls in large measure the cost of the survey. It will depend on the purpose and scale of the survey, prior knowledge of the region, surveyor's experience, the complexity of the region and the sampling scheme chosen. The number of borings will always be limited by cost. Decisions on numbers again depend on the type and purpose of survey.

The minimum type and density of sampling for qualitative surveys is based largely on the project team's experience and judgement, and may be agreed in consultation with the client. Tables 14.2 and 14.3 outline the main classes of observation and the effort devoted to each during general purpose qualitative surveys. The minimum density of sampling for quantitative surveys will be based on statistical analysis of data or interpretations of field results until a desired level of prediction is achieved. Table 14.4 provides an approximate guide to sampling densities for conventional mapping in landscapes of moderate complexity.

Quality

All information exhibits uncertainty, and this can be expressed quantitatively or qualitatively (see *Chapters 3*, *20* and *24*). For example, a site's location might be inaccurate, data might be recorded incorrectly or laboratory analysis might be rough. The uncertainty of the final output depends on the uncertainties of the input.

Table 14.2 Main classes of observation

Class	Observation type	Description
I	Detailed soil profile descriptions	Detailed morphological and site descriptions that can be used to characterise the main soil and landscapes in a survey area
II	Deep borings	Deep borings examine material below the normal depth of soil description and are important where subsolum and substrate properties influence land use. They are essential if irrigated land uses are proposed. Deep boring allows consideration of factors such as deep impermeable or permeable layers, salt accumulations, groundwater depth and salinity
III	Profiles for sampling	Profiles where samples are taken for analyses. These may be done off-site in the case of chemical and some physical analyses, or on-site for other physical measurements (e.g. hydraulic conductivity). Sampling is usually conducted to characterise typical or reference soils in a survey, or to target selected soil attributes such as fertility, sodicity or salinity Physical and chemical analyses are expensive and must be well targeted and clearly specified
IV	Mapping observations	Mapping observations are brief observations to confirm mapping boundaries, soil-type distributions or other characteristics being mapped in the survey. They are always brief, and make up most sites in most surveys

When a survey is specified, uncertainties at all stages should be understood by both the surveyor and the client. Questions such as ‘how well will this map represent reality and how well will the data predict properties of the land?’ need to be answered. Uncertainty is often hard to determine, especially when qualitative methods are employed. This should not prevent an attempt to estimate it. The default estimates of uncertainty used in the Australian Soil Resource

Table 14.3 Recommended percentages of ground observation classes for general purpose surveys (after Gunn et al. 1988)

Survey intensity and cartographic scale	Observation class			
	I Detailed profile descriptions	II Deep borings	III Profiles for sampling	IV Mapping observations
Very high intensity (>1:10 000)	10–30%	1–5%	1–5%	60–88%
High intensity (1:10 000 to 1:50 000)	10–30%	1–5%	1–5%	60–88%
Medium intensity (1:25 000 to 1:100 000)	15–35%	1–5%	1–5%	55–83%
Low intensity (1:100 000 to 1:250 000)	15–40%	1–5%	1–5%	50–83%
Reconnaissance/overview (>1:250 000)	30–90%	1–5%	1–5%	<60%

Table 14.4 Recommended ground observation densities for conventional qualitative land resource surveys (after Gunn et al. 1988)

Cartographic scale	Area per observation			No. observations per unit area		
	Recommended range		Minimum acceptable	Recommended range		Minimum acceptable
	Upper	Lower	high	low		
	Area (cm ²) of published map per site					
All scales	1	2 Units (ha/site)	4	1	0.5 Units (sites/ha)	0.25
1:10 000	1	2	4	1	0.5	0.25
1:25 000	6.25	12.5	25	0.16	0.08	0.04
1:50 000	25	50	100	0.04	0.02	0.01
		Units (km ² /site)			Units (sites/km ²)	
1:100 000	1	2	4	1	0.5	0.25
1:250 000	6.25	12.5	25	0.16	0.08	0.04
1:500 000	25	50	100	0.04	0.02	0.01

Information System provide a starting point (McKenzie et al. 2005). The uncertainty in qualitative surveys can be substantially reduced by enforcing consistent guidelines and standards.

Try to collect information to an accuracy, precision and resolution appropriate to the use of the outputs.

Positional accuracy of spatial data

Understand the methods used for locating spatial data and record them in the metadata to ensure users know positional accuracy. This will encourage use of the data. Include the following information for existing and new point data:

- *method of location* (e.g. GPS, digitised from aerial photograph, map)
- *datum* (from 1 Jan 2001 it should be GDA94 the Geocentric Datum of Australia)
- *coordinates* – these can be either geographical (latitude and longitude) or Universal Transverse Mercator (UTM consisting of a Zone, Easting and Northing).

Other datums used in the past (e.g. AGD66, AGD84) have caused considerable confusion, so record the datum (and date) with the coordinates. Most point locations are now recorded by Global Positioning Systems (GPS), and where differential GPS is used, its type and expected accuracy should be recorded (see *Chapter 16*).

Polygonal information, in addition to the datum and coordinates used, should include reference to the method of capture (e.g. via digitising from 1:25 000 colour photos, 1:100 000 maps or satellite images or direct tracking using a GPS).

Spatial and temporal data

Land resources vary in space and time. Some data are clearly spatial or temporal. These are exemplified by a soil map and climate station data, respectively. Others blur the distinction (e.g. a map summarising trends in soil change). Commissioners of surveys are increasingly seeking information on trends in land condition. There is a widespread but mistaken belief that conventional surveys of land resources can provide an efficient and effective baseline for monitoring change. Strategies for monitoring land condition are distinct from those for

mapping. See *Chapter 30* for an account of methodology and strategies for monitoring change in land resource condition.

Survey rate

The rate of survey can be expressed as the area surveyed per unit time. It will vary considerably depending on a several factors including:

- the purpose of the survey and the associated level of attribute measurement
- the skill and experience of the surveyor(s)
- the quality of the resource information (photographs, remotely sensed images)
- the accessibility of the terrain
- the type of survey (scale and design) and sampling scheme
- the ease of sampling (soil texture or the amount of rock or gravel, which may affect the sampling rate)
- the percentage of project time spent in the field.

Table 14.5 provides a guide for the rate of field survey based on 1 ground observation per 2 cm² of published map, which is near the minimum density recommended in Table 14.4.

Survey timing

Weather or soil moisture conditions may limit when surveys can be done. For example, field-work in much of northern Australia is impractical in the wet season. Conversely, in the south, the soil may be too dry and hard to sample during the summer or too wet to access during winter. Staff availability will be also affected by public holidays. Schedule the field program when resources are available and field access is assured. See *Chapters 15* and *18* for an outline of survey resources and logistics).

Data collection techniques

Techniques for data collection will often be specified as part of the survey method. For the field-based component, options include the use of traditional field sheets where the data are either manually entered or scanned into a computer later, or by recording the data digitally in the field on laptop computers, digital notepads or automated dataloggers (see *Chapter 16*).

Resources

The resources required for the survey will be determined by the survey design. Start with the cost and density of observation because the one will determine the other. After the resources necessary for the design have been calculated, check them against the available resources and budget. If funds and resources are insufficient, modify the expected outcomes or survey design using an iterative process until a suitable compromise has been reached with the client. You might have to compromise, but if so make sure the compromise is between available resources and expected outcomes and not between available resources and design. The latter will lead either to either unfulfilled outcomes or time and cost overruns.

Physical resources

Operating

Operating resources are all the non-staff and non-capital costs associated with a project, including:

- materials (consumables)
- equipment (tools, computers, etc.)

Table 14.5 Guide for calculating rates of the field component of qualitative soil surveys (based on 0.5 ground observations per cm² of published map, the lower end of range recommended in Table 14.4)

Survey intensity and cartographic scale	Observation Class I		Observation Class II		Observation Class III		Observation Class IV		Survey rate	
	Detailed profile descriptions		Deep borings		Profiles for sampling		Mapping observations			
	% of total observations	No. per day	% of total observations	No. per day	% of total observations	No. per day	% of total observations	No. per day	ha per field day	ha per year ¹
Very high intensity (> 1:10 000)	10	7	3	4	2	4	85	25	40	4000
High intensity (1:10 000 to 1:50 000)	15	7	3	4	2	4	80	20	210	21 000
Medium intensity (1:25 000 to 1:100 000)	20	7	3	4	2	4	75	15	640	64 000
Low intensity (1:100 000 to 1:250 000)	25	7	3	4	2	4	70	11	1900	190 000
Reconnaissance and overview (> 1:250 000)	40	7	3	4	2	4	55	9	10 000	1 000 000

¹ Assumes 100 field days per year.

- infrastructure (buildings and their maintenance, electricity, telephone, etc.)
- travel (e.g. vehicles, airfares)
- accommodation.

The costs associated with operations are often divided into indirect and direct costs. *Direct costs* specifically relate to the project, for example, travel, accommodation and survey equipment. They can be directly included in the project costs. The employment of consultants is usually treated as a direct operational cost. *Indirect* or *overhead costs* are those of maintaining the capability of the provider to conduct the work but not directly related to the project – for example, the costs of maintaining the provider’s infrastructure of buildings, computers and telephones. They are typically recovered by adding a percentage to the project cost.

Capital

Capital resources are major operational items (usually defined by a threshold value) and they will include vehicles and computers. Agree during the project’s specification on the definition of capital items, and on their depreciation and eventual disposal. It may be appropriate to hire or lease expensive capital items rather than purchase them. In this case, the cost of leasing is an operational cost.

Existing information

Information required by the project can include digital data (maps, reports, databases), printed products (reports, air-photos, maps) or advice. Make sure the cost of accessing information is included in the budget. Be careful to identify intellectual property issues relating to this information.

Locate existing information early in the life of a project. It takes time and, therefore, costs money. This is sometimes incorporated into the scoping phase of a project. At other times the information has value to the provider beyond the project under consideration, in which case the provider and the clients might agree to share costs.

Human resources

Staff suitability and availability

Good people are vital to success. Factors to be considered and specified include the following.

Staff qualifications and accreditation

The technical or professional qualifications of project staff may be specified in the project. Sometimes a client requires the names of staff. There may also be mandatory qualifications required, such as accreditation to use a drilling rig or drive special types of vehicle, which will restrict who can work on the project. A project may require that survey work be done only with accredited staff (e.g. Certified Professional Soil Scientist with the Australian Soil Science Society Inc. or similar).

Staff knowledge and experience

Staff with unique knowledge, specialised skills or certain experience may be specified in a project.

Staff availability

Availability of staff must be considered in conjunction with the identified tasks. Issues such as sharing resources between projects, staff management, leave entitlements and contingencies for resignations or transfers need to be considered when the timetable is drafted.

Recruitment and selection of staff can significantly delay the start of a project. Similarly, departure of a staff member during a project can cause major disruption. These issues can be considered in the process of risk management.

Staff training

Training may need to be included in a project to ensure that legal obligations are met or duty of care is demonstrated. At a generic level this may include safety training or an understanding of equal employment opportunities. Staff may require specialist technical training to be able to meet the project's requirements. The time and cost of this training must be taken into account, and, where appropriate, shared between provider and client. Staff training also enables the provider to maintain or improve its capacity to supply a service in the long term.

Staff management

Make sure the manager supervises performance, and can handle problems like claims for accidental injury. This is an internal issue for the provider's organisation, but it can have a major impact on the ability to meet agreed timetables. A client may wish to consider the staff management practices of a provider before entering into a contract; they may also wish to see staff performance reports to ensure best outcomes. These reports may be confidential and require approval of the staff concerned before they are released.

Project management

The topic of project management is a volume in its own right so the standard texts listed (see *Introduction*) can be consulted. The following is a summary and checklist.

Project planning

Good planning is essential for success. The degree of planning depends on the complexity of the project, but all projects will benefit from time spent in planning. Planning ensures that resources are managed within a specified budget and time-frame to achieve the desired outcomes.

Project leadership

Leadership provides direction and management of human and physical resources. Good leadership can also provide benefits beyond the survey, including a vision of possible future uses of the work, and ensuring the project is structured to maximise future benefits.

Roles and responsibilities

Clearly define the roles and responsibilities of the provider and the client before the project begins and ensure that all parties understand them. You may require written partnership agreements to clarify these issues.

The roles and responsibilities include client responsibilities for the timely provision of resources, including information, logistics, funds and access to properties, or client collaboration where the client undertakes part of the project work. Alternatively, the provider may have reporting requirements (see *Outputs*) to the client. The client and provider may also need to agree on protocols for accessing data and information obtained by the survey.

Whatever the agreement, all inputs must be clearly stated and scheduled to allow the project to proceed according to the Terms of Reference.

Stakeholder liaison and consultation

An important contribution to success can be in-kind support from the community or other interested parties. This support can include:

- permission for access to land
- logistic assistance
- local knowledge
- establishing contacts
- confidence, trust and support of land-holders.

Support from communities and stakeholders, especially for major projects, is usually achieved through comprehensive consultation or some other forum for including their concerns and suggestions. Surveyors must understand and support the project, and then communicate the benefits to the broader community.

Quality assurance and control

The technical specifications of the project will state the quality standards expected for the work being undertaken. Make sure there are set methods and procedures to monitor these standards, review the work and solve any problems. The project may need to comply with national or international environmental or other standards.

Project monitoring – milestones and reporting

Milestones include the completion of products such as maps and survey reports, as well as progress reports on the field component or development of methods. The type and frequency of reporting will depend on project complexity and the client's requirements.

It is usual for payment to be linked to satisfactory reporting, delivery of milestones or both. Reporting is an essential way of checking that the project is on track and likely to deliver on time and within budget.

There may be financial or other penalties for the late or non-delivery of agreed milestones, and in some cases an independent arbitrator may have to resolve disputes. If this is a possibility, then agree on a process of arbitration in the Terms of Reference.

There should be provision for contingencies when milestones cannot be delivered as a result of circumstances beyond the control of provider or client. Special clauses need to be included in the contract to cover unforeseen circumstances such as war, floods, disease or other disaster that restrict the timely conduct of the project.

During longer term projects, review the milestones as circumstances vary. Changes in technology, methods, staff and other factors may lead to revisions during the life of the project. This flexibility allows for continuous improvement during the project.

Project evaluation

After completion, a client may require an assessment of the effectiveness of the project. This assessment is often done by an independent party. It provides feedback to improve future project specifications or enable assessment of the provider.

Communication planning

Prepare a plan for communicating results during the planning phase, and adhere to it throughout the project. Base the plan on an understanding of the client's needs. See *Chapter 32* for principles of communication planning and implementation.

Constraints and assumptions

Delivery of project outputs depends on several constraints and assumptions. Use the techniques of risk assessment and management to identify and understand these constraints and assumptions when you formulate the project.

Risk assessment and management

Assess the risk for the project and, where the risks are significant, reach agreement on an appropriate response. Typical risk assessment and management proceeds as follows:

1. *Identify the main risks* affecting the conduct of the survey. For example:
 - military conflict during an overseas operation
 - natural catastrophes that restrict access (e.g. flood, fire, disease)
 - landholders withdrawing access or changing access conditions
 - departure of staff
 - accident and injury to staff
 - collaborators withdrawing cooperation or resources
 - withdrawal of one or more clients (even with penalty clauses, these actions may affect the viability of the survey)
 - damage to essential equipment
 - strikes in service organisations or the financial collapse of organisations or contractors
 - bad weather
 - unrealistic expectations
 - loss of data.
2. *Analyse and assess* the likelihood of the risks occurring along with their potential impacts on the project. Decide whether the risk is worth further consideration, and, if so, what action is appropriate.
3. *Develop an action plan* to deal with significant risks. List how, when, and where solutions should be implemented and by whom.
4. *Monitor and review* the risk management plan and its documentation. Comprehensive methods for risk analysis are presented in Australian Standard 4360:2004.

Outputs

Outputs from the project can be in a variety of forms. For example, written reports, maps, digital data, verbal advice, presentations and seminars. See *Chapter 32* for defining the method of delivery. Remember that report writing and quality assurance take time.

Data management

Data are valuable, and the potential for re-analysis by digital techniques makes the acquisition, storage and protection of the many data from land resource surveys a significant issue (see *Chapter 25*).

Data standardisation

Set standards for the collection and storage of data. Good standards exist for field description (McDonald et al. 1990), soil chemical (Rayment and Higginson 1992) and soil physical methods (McKenzie et al. 2002). However, the standards for describing land units and land evaluation differ widely between agencies. Some degree of standardisation is desirable.

Data transfer

It may be necessary to set protocols for exchange of data between the provider and client and to compare information collected in different systems. The long-term benefit of such a protocol is effective sharing of data between organisations. The current protocols for data transfer relating to soil profiles and sites are described in Kidston and McDonald (1995) and these in turn rely on the Australian Soil and Land Survey Handbooks (McDonald et al. 1990; Rayment and Higginson 1992; Isbell 2002; McKenzie et al. 2002). McKenzie et al. (2005) specify minimum data sets for soil profiles and land units for the Australian Soil Resource Information System. If successful, these will be the basis for a more complete transfer standard for land resource data (see *Chapter 25*).

Data reliability

Ensure statements on spatial accuracy are given in reports and on maps. This has not been part of standard practice in Australia, partly because of the technical difficulty of providing reliable estimates. It is routine in some countries to specify acceptable percentages for inclusions within map units. These inclusions are usually differentiated into: (a) those that affect interpretations of land use, and (b) other soil components so similar to the mapped soil that major interpretations are not affected (e.g. Soil Survey Division Staff 1993).

Data management and access

Manage and store data securely as they are recorded. Have a clear agreement with the client on access, ownership and responsibilities for management (see *Chapter 25*). The Australian and New Zealand Land Information Council (ANZLIC) define three key roles in relation to data management.

1. The *data owner* has ultimate control of data access, use and pricing.
2. The *data custodian* is an organisation or person responsible for the development, or management, or both, of a data set. The custodian has the right to determine the conditions of use for data.
3. The *data sponsor* is an organisation (often a government agency) or person having a special interest in ensuring that important data are widely available. Sponsors may provide leadership in developing standards for content, quality and transfer of data, and coordinate custodians to minimise duplication of effort and maximise benefit.

Make sure these roles are clearly defined during the initial design of the project. One organisation or person may include the three above roles, and for simple projects the separate roles of custodian and sponsor might not be required. Consult *Chapter 25* during the specification process for data management and access.

Data storage

Data need to be stored in organised systems for easy retrieval and interrogation. Geographic Information Systems (GISs) and databases, in which land unit and site data are digitally stored in a structured way, serve well. Plan for this at the outset and assign adequate resources. Digital data sets are often updated, so make sure systems are in place for time-stamping and version control. See *Chapter 25* and the most recent protocols for the Australian Soil Resource Information System (ASRIS 2007).

Data backup and archiving

Backup and archiving are important and often overlooked. Large amounts of information have been lost because of inadequate backup and archiving. All information relating to a

project, including the project specifications, relevant working documents, project outputs and metadata must be correctly stored and archived. Store valuable data in secure locations, or at least keep multiple copies in different locations. Specify arrangements for the regular backup of data while the work is in progress.

Archiving specimens

Establish procedures for safe storage of soil, rock, plant or other physical material collected during the survey. Guidelines are available for archiving soil specimens and other materials (see *Chapter 30*). Consider lodging specimens with the CSIRO National Soil Archive.

Metadata

Metadata are literally data about data. See *Chapter 25* for a full account of the importance and demands created by metadata. Metadata are critical for online cataloguing and retrieval of information. They typically describe the contents, location, physical attributes, type (e.g. text or image, map or model) and form (e.g. print copy, electronic file) of data. A typical set of metadata for a land resource survey dataset will include:

- title
- surveyor
- owner of data
- contact details
- description of survey
- geographical extent
- data currency (durability of data)
- data set status (progress, maintenance and update frequency)
- access to data (format used for storage, available format types, access constraints)
- data quality (lineage, positional accuracy, attribute accuracy, logical consistency, completeness)
- metadata date
- additional metadata (e.g. datum, projection, grid).

Recording of metadata about a project is essential. In Australia, use the ANZLIC metadata guidelines (ANZLIC 2006). It may be necessary to include extra fields to meet the needs of land resource data.

Project documentation

An important, but often neglected, component of a project is documenting the methods, metadata statements and any aspects of the project that would assist future work related to the project or similar projects in the future. The transition to quantitative and digital methods is making this difficult. Archive project documentation, including the project specifications and outputs, in both hardcopy and digital form. Ensure final reports and related publications are lodged with major libraries.

Financial and legal considerations

Several financial and legal issues need to be considered in a project. Some are as follows.

Contract

In most cases a contract is required. The most basic will specify the Terms of Reference and a payment schedule based on the project's milestones. The contract for major projects may be

comprehensive, including details on methods, outputs and penalty clauses for not achieving milestones on time. For larger projects, managing the contract is a task in itself and requires resources.

Cashflow and payment schedule

Payments will usually be linked to the achievement of milestones specified in the contract. The timing of these payments affects the cashflow of the project, and this can influence the viability for the provider and purchaser.

Relationship to legislation and standards

The project may be required to comply with local, national or international standards, or government legislation, policies and guidelines. See *Chapter 31* for a description of the legal and planning framework.

Occupational health and safety and equal employment opportunity

Each jurisdiction in Australia has legislation requiring employers to provide safe and healthy workplaces and to ensure fair employment opportunities. Some of these aspects are discussed further (see *Chapter 16*).

Legal liabilities

The provider requires some form of legal liability insurance to provide indemnity if things go wrong. The onus may also be on the client to provide safe access or working environments. This comes under a general requirement for due diligence and duty of care.

Access to properties

Agreements, preferably in writing, need to be obtained from landowners to gain access to properties, and to deal with any intellectual property or commercial issues (e.g. data demonstrating land degradation on a property is usually sensitive). Again, make sure insurance arrangements for the project staff and landowners are clearly defined.

Intellectual property rights and confidentiality agreements

Intellectual property (IP) issues must be identified and addressed in the contract where appropriate. The IP can include the data collected during a survey, any methods developed or other outputs with a monetary value. Agreements may include clauses in the project contract or special confidentiality agreements between the client and the provider.

In general, the person paying for the project owns the IP unless it has been explicitly assigned to another part through contractual arrangements. In the case where there is joint funding (through monetary or in-kind support), IP ownership is generally distributed in proportion to the funding. Ownership of IP is less clear where information is collected by public institutions using public funds. ANZLIC provide principles on access to spatial data and pricing, especially for information of public good (ANZLIC 2006).

A third party, not directly involved in the project, may wish to use the results. In such circumstances, establishing IP ownership at the start of the project minimises conflicts over access and costs of the information. Further useful information is available from IP Australia (IP Australia 2006).

Signatures

All affected parties must sign the contract or agreement.

Supporting documentation

Supporting documentation strengthens the Terms of Reference and the project. It can include background information about the survey method and techniques, and the survey area.

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Survey resources

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Introduction

This chapter describes the skills, equipment and information required for a professional survey. Adequate resources are essential, and in practice they set limits to the design and possible outcomes.

In Australia it has become common practice for a single field scientist to be responsible for planning and executing most survey tasks, and the success of a survey now depends heavily on his or her skills. In most surveys, however, and especially larger integrated ones, an interdisciplinary team approach brings benefits. The quantitative methods described in the *Guidelines* (e.g. see *Chapters 20 to 26*) demand a broad range of skills and they rarely reside within a single person.

Human resources

In a small survey, a pedologist (or equivalent field scientist) and their field assistant do most of the work. The pedologist is expected to have skill in pedology and survey methods, as well as an understanding of other disciplines such as geology, geomorphology, hydrology, agronomy, botany and data management. Larger surveys are the province of teams, typically comprising staff with diverse and specialised disciplinary skills.

The success of surveys depends heavily on the type and level of skills of the scientific staff. For efficiency and reliability, experienced professional staff should conduct field operations. It is a mistake to commission graduates with little field experience to lead surveys. Such people need to learn from experienced practitioners before they can lead and complete the surveys to a high standard. However, do not appoint mentors with field experience but no capacity to change.

A team approach calls for members having, at a minimum, skills in information management, statistics and remote sensing. Without coordination and team management, the advantages of an integrated approach will fail to emerge.

In addition to recruiting good scientific staff, the authors recommend that clients, stakeholders and support staff become involved along the following lines.

Clients

Clients are responsible for defining the purpose and expected set of outcomes of the survey. In collaboration with the provider, they lead in developing the terms of reference (see *Chapter 14*). Of course, the client will have contractual obligations to provide funds and, possibly, resources (e.g. staff, equipment, data). The client must understand the purpose of the survey, how the outcomes will benefit its operations, and should have some technical understanding of project design and survey procedures (or have access to a competent advisor).

Stakeholders

Stakeholders are interest groups or individuals – apart from the client – who can benefit from, or be affected by, the project. Stakeholders range from individual landholders to communities, industry groups, and governments at various levels. For general purpose surveys for which there are several stakeholders (typical of projects funded publicly), it is helpful to establish a reference group to represent the interests of all stakeholders. An important contribution to a project can be in-kind support from stakeholders. Seek support, for example, in the form of local knowledge, assistance with logistics, connection to local community networks and access to land. Involvement by stakeholders in project procedures will depend on their skills and ability.

Support staff

Support staff are necessary for field operations, especially to work machinery and to work in remote areas (see *Chapter 16*). Field technicians, less experienced pedologists, stakeholders and clients can assist the field scientist. This helps accelerate operations and enhances safety. With time, these people may be able to carry out, under supervision, survey work themselves.

Office-based support staff are needed for administration (project registration, work place health and safety, human resource management, legal support), for running computers (geographical information systems, maintenance and upgrades of computing facilities), and for preparing publications (editing and graphics). Laboratory support is also required.

Although experienced and expert staff are necessary, part-time involvement may be enough. In large organisations, support staff and other trained people can be shared between surveys, although they must communicate with one another and the leader needs to coordinate their contributions. If the required skills are not available internally, obtain contracted experts from outside the organisation. This is the project manager's job.

Skills

The skills required for qualitative and quantitative surveys are listed in Table 15.1. As noted earlier, a survey may involve one person with the necessary range of skills, or several people each with one specialised skill.

Project management

All land resource surveys require good project management (Table 15.1). Effective leadership and good communication are essential in survey teams. The leader provides direction and motivates staff. The hallmarks of effectively managed projects are that they:

- attract good recruits
- have high standards
- have staff who are aware of the required information
- present results that have been systematically tested and checked
- provide training
- adhere to budget
- deliver on time
- exhibit excellence in reporting and communication (see *Chapter 32*).

Table 15.1 Skills required and time involved for qualitative and quantitative land resource surveys. F: skills required full time (>60%) or continuously at regular intervals; P: skills required part time (20–60%) or for short periods at regular intervals; O: skills required occasionally (>20%) or intermittently. Where an element of the table covers several survey types, text in *italics* applies to all the included survey types except where indicated by a dash.

	Qualitative survey			Quantitative survey	
Skill	Integrated	Free	Stratigraphic	Environmental correlation	Geostatistical
Project management					
Communication, verbal	F effective communication; public speaking; liaison				
Communication, written	P effective reporting and promotion of results				
Group facilitation	O meeting procedures; organise events and extension activities				
Human resource management	F staff recruitment; implement effective training/mentoring; establish staff roles/responsibilities				
Survey management	F establishment of Terms of Reference; resource allocation; budget monitoring; progress reviews; establish and review milestones; task planning; quality control; leadership; workplace health and safety; monitoring team performance; motivation; conflict resolution; networking; ensure effective use of equipment				
Strategic planning	O identifying collaborators; risk analysis; future direction and use of results; align survey with organisational policies and priorities				
Pedology and survey method					
Land evaluation	P determination of critical limits for land attributes that define suitability/capability classes for a range of uses		O determination of critical limits for land attributes that define suitability/capability classes for a range of uses	P determination of critical limits for land attributes that define suitability/capability classes for a range of uses	P determination of production potential or environmental functioning using quantitative attributes
Landscape processes	F correlation of soil properties with processes	P correlation of classification system to processes	F correlation of soil layers with landscape genesis	F correlation of soil properties with processes	F correlation of soil properties with environmental variables

(Continued)

Table 15.1 (Continued)

Skill	Qualitative survey			Quantitative survey	
	Integrated	Free	Stratigraphic	Environmental correlation	Geostatistical
Land management	P <i>knowledge of indicators of soil condition and their influence on soil performance</i>	P	P	P	–
Landscape modelling	F <i>development of soil–landscape models: conceptual</i>	P conceptual	P conceptual	F explicit	–
Map interpretation	O <i>interpretation of geometry (contours, reference, etc.)</i>	O	O	O	–
Pedology	F <i>recognition, description and interpretation of: soil properties</i> <i>understanding of: spatial variation</i>	F soil properties and genesis –	F pedoderms and genesis –	F soil properties spatial variation	P – spatial variation
Photograph interpretation	F <i>interpretation of patterns in photographs and images</i> <i>navigation/site location</i> <i>stereoscopic interpretation</i>	F	P –	F – –	–
Resource planning	P <i>allocation and appropriate management</i>	O	O	P	–
Soil classification	F <i>development of map units based on: mapping sites and landscape processes</i>	F large number of sites prior to mapping	F layer genesis	F sites and landscape models	–
Soil chemistry/physics	P <i>interpretation of laboratory data and correlation to: soil properties</i>	P soil classification	P layers	P soil and environmental properties	P soil and environmental properties
Survey techniques	F correlation of point data with observable attributes	F mapping of units and boundaries based on soil classification	F correlation of point data with observable surface features	F correlation of point data and environmental variables	F interpolation of data from a large number of quantitative sites

	Qualitative survey			Quantitative survey	
Skill	Integrated	Free	Stratigraphic	Environmental correlation	Geostatistical
Geology					
Geophysics	O <i>interpretation of geophysical data:</i> seismic bore log radiometric electromagnetic	O seismic bore log radiometric electromagnetic	O seismic bore log radiometric electromagnetic	F seismic bore log radiometric electromagnetic	O seismic bore log radiometric electromagnetic
Field identification	P <i>identification of lithology, structure, stratigraphy, formation, minerals, degree of weathering and superficial layers; correlation to:</i> landscape development	P soil classification	P layer genesis	P landscape development	O –
Map interpretation	P <i>geological maps</i>	O	O	P	P
Geomorphology					
Geophysics	P correlation of site geomorphology to remotely sensed geophysical data			F correlation of site geomorphology to remotely sensed geophysical data; development of explicit models	F
Landscape development	F <i>description of land forming processes and chronologies; distinguishing accelerated processes; development of conceptual models; correlation to:</i> soil, geology and hydrology at site	P soil classification	F soil, geology and hydrology at site	–	–
Regolith	O description of properties, degree and age of weathering	–	F description of degree and age of weathering; determination of origin and properties of layers	O description of properties; correlation with geophysical data	–

(Continued)

Table 15.1 (Continued)

	Qualitative survey			Quantitative survey	
Skill	Integrated	Free	Stratigraphic	Environmental correlation	Geostatistical
Hydrology					
Water quality	O	O	O	O	–
	identification of interaction between environmental variables (soils, landscape, climate) water quality				
Groundwater flow systems	O	O	O	P	development of explicit models
	description; understanding interaction with land management				
	–	–	–	–	
Hydrological data	O	O	O	O	P
	collection and interpretation of surface and subsurface data (quality, quantity, dynamics)				
Hydrology	O	O	O	P	P
	assessment of parameters (runoff, deep drainage, soil storage)				
	–	–	–	use of pedotransfer functions to predict dynamics	
Agronomy					
Agronomy	O	O	O	O	
	provision of plant and machinery specifications for land evaluation; crop management				
Modelling	–	–	–	P	F
	crop production modelling; determination of crop water/nutrient requirements and solute tolerance				
Ecology					
Ecology	O	O	O	O	P
	assessment of interactions between biota and: physical resources soil units landscape layers				
	assessment of affect of biota on soil chemical/physical properties; use of indicators of degradation or landscape health: –				
	–	–	–	physical resource	–
	–	–	–	development of explicit models	–
	–	–	–	–	interpolation
Landscape planning	O	O	O	O	–
	linking biodiversity to land management; specification of management requirements				
Taxonomy	O	O	O	O	–
	species identification and classification				

	Qualitative survey			Quantitative survey	
Skill	Integrated	Free	Stratigraphic	Environmental correlation	Geostatistical
Botany					
Modelling	–	–	–	F correlation of floristics/ structure with soil/ landscape properties	–
Floristics and structure	P <i>assessment of floristics and structure; identification of indicator species for degradation</i>	P	P	P	
Mapping	F <i>correlation of photograph patterns and floristics or structure with: soil and landscape properties</i>	F	P soil classification	– soil layers	–
Taxonomy	P <i>species identification and classification</i>	P	P	P	–
Vegetation evaluation	O <i>linking plant growth requirements with: land attributes</i>	O soil units	O soil layers	O land attributes	O land attributes
Vegetation management	O <i>evaluation of management requirements for reproduction, fire, weeds</i>	O	O	O	–
Soil chemistry and physics					
Laboratory/site analysis	O <i>accurate analysis of specimens; interpretation of results</i>	O	O	O	P
Soil chemistry/physics	P <i>correlation of results with land management and: soil morphology</i>	P soil classification	P soil layers	P soil morphology	–
	<i>development of: conceptual models</i>	–	–	explicit models	
Sampling	O <i>sampling procedures and site selection</i>	O	O	O	P
Data management					
Basic computer skills	P <i>data entry; awareness of program functions and operations</i>	P	P	F	P

(Continued)

Table 15.1 (Continued)

Skill	Qualitative survey			Quantitative survey	
	Integrated	Free	Stratigraphic	Environmental correlation	Geostatistical
Data management	P <i>database organisation and structure; database updating; networking; integration of software and version control</i>	P	P	F	P
Querying	O <i>database analysis</i>	O	O	F	F
Relational database design	O <i>database development</i>	O	O	P	P
Geographical Information Systems (GIS)					
Cartography	O <i>map design and preparation; projections/datum; digitising</i>	O	O	O	O
Data analysis	–	–	–	P analysis and manipulation of remotely sensed data	P
GIS	O <i>manipulation, analysis and presentation of spatial data; product creation; integration of software and data</i>	O	O	F	F
Modelling	–	–	–	F	F
Statistics					
Environmental correlation	O <i>correlation of qualitative and quantitative (e.g. chemical/physical) spatial data with: soil properties</i>	O soil classification	O soil layers	P environmental or soil properties identification of minimum and validation datasets	P environmental variables
Theory	O <i>familiarity with statistical theory, analysis, measurement and data sources</i>	O	O	P	P
Spatial analysis	–	–	–	P development of explicit statistical models; assessment of variation, certainty, accuracy; statement of assumptions	P
Survey method	–	–	–	P project design (data type, collection method); identification of variables; identification of method of analysis; calibration of pedotransfer functions and numerical classification systems	P

Pedology and survey method

The pedologist needs to:

- appreciate processes of landscape evolution and pedogenesis
- be able to select and implement the most appropriate survey method (see *Chapter 3*)
- competently describe and assess soil and land attributes (including classification systems for horizons and profiles).

Although it is true that the skills for a qualitative survey differ from those for a quantitative one (Table 15.1), it is nevertheless unacceptable for a pedologist doing a qualitative survey to be ignorant of sampling and statistics. Likewise, a pedometrician undertaking a quantitative survey must understand landscape evolution and pedogenesis to avoid inappropriate methodology.

The pedologist needs to be able to develop and test models of soil distribution (see *Chapter 5*) because these form the core of many aspects of survey: site selection, boundary placement, land suitability assessment and formulation of recommendations on land management.

In qualitative surveys, mapping accuracy depends on the skills of the surveyor. Always aim to use methods that are explicit, consistent and repeatable. This, in conjunction with independent validation (see *Chapter 18*), provides the basis for quality control.

The surveyor may be asked to participate in post-survey activities. Beckett and Bie (1978) astutely noted that the most useful source of information is often not the map or report but the surveyor. Be prepared to provide post-survey support to clients and stakeholders. This can include selection of monitoring and experimental sites for agronomists, provision of explanations on landscape processes to scientists in related fields and training in 'land literacy' for community organisations.

Geology

Geology is fundamental to soil and landscape development (see *Chapter 4*). Understanding the key relationships between soil properties and parent materials helps mapping greatly (see *Chapters 4, 5, 10, and 18*). It is a major asset to have training and experience in the identification of lithology, geological structures, stratigraphy and processes of weathering and alteration.

The standard, nationwide geological mapping at a scale of 1:250 000 or larger provides valuable data for surveys. Expert skills are usually necessary for interpretation and relating maps to field observations. Geological maps often depict materials at great depth, but the degree of weathering or alteration is often poorly represented – and this can limit their value for assessment of land resources (see *Chapter 4*). Special skills are required for interpreting geophysical data such as radiometric, magnetic, electromagnetic, seismic, bore logs and geoscience literature. Standard references include Taylor and Eggleton (2001) and Press et al. (2004).

Geomorphology

Incorporating both a pedologist and a geomorphologist into a survey team is often effective and can result in surveys of enduring value (e.g. Gunn et al. 1967). In intense surveys of small areas, the role of geomorphology will normally be less but make sure it is not ignored.

Understanding landscape evolution helps produce better surveys (see *Chapter 5*). An ability to recognise, describe and interpret evidence for different geomorphological agents in the field is invaluable. Important geomorphological agents include gravity, precipitation, streamflow, wind, ice, standing water, internal forces (e.g. tectonics, volcanism), biological agents and, in rare cases, extraterrestrial agents (e.g. meteor impact). These skills are especially important for recognising superficial surface or buried layers, inferring regolith properties (especially thickness), and identifying accelerated processes such as erosion and salinity associated with land use change.

In qualitative surveys, expertise in air photograph interpretation and analysis of site indicators is needed to interpret landscape development (see *Chapter 10*). Geophysical information is now equally significant, and relevant skills are called for. As an example, terrain analysis in association with radiometric or other geophysical data usually provides an excellent basis for identifying geomorphical processes and the origin of soil materials (see *Chapters 6 and 13*).

Valuable references on geomorphology include Williams et al. (1998), Summerfield (1991), Thomas (1994) and Taylor and Eggleton (2001).

Hydrology

Knowledge of hydrology is almost essential to most surveys (see *Chapter 7*). Surface and near-surface hydrological behaviour is a result of interactions between weather, landform, vegetation, land management, and the hydraulic properties of soil, regolith and underlying substrate. An appreciation of these sometimes complex interactions helps solve many practical problems. Hydrological knowledge pertains to mass movement of soil, landscape development and weathering processes. If a survey outcome is water resource management, then acquire the services of a surface hydrologist or groundwater specialist. Where direct hydrological data are lacking, specialised skills in modelling the water balance are needed to estimate rates of evaporation, transpiration, runoff and deep drainage, along with movement of solutes, sediments and nutrients.

Groundwater movement is often difficult to quantify. Analysis usually relies on sparse observations from a few piezometers or wells and supported by sophisticated mathematical modelling. Predicting groundwater movement and quality relies on an understanding of geology, geomorphology geochemistry, hydrogeology, microbiology, hydrology and numerical modelling. There is no substitute for long-term data and monitoring.

McKenzie et al. (2002) and Hillel (2003) can provide accounts of soil hydrology and measurement, while Freeze and Cherry (1979) and Maidment (1993) are comprehensive texts on groundwater and hydrology.

Agronomy

If the information you seek may end up in the realm of agricultural decision-making, secure the services of an agronomist. Skills in agronomy (crop, pasture, horticulture, forestry) feed into developing land suitability ratings and into providing recommendations on land management. Agronomists understand the requirements for plant growth, specific tolerance limits, specifications for farm machinery, and the effect of crops on landscape processes. Their skills contribute to hydrological modelling through knowing how vegetation affects the water balance of a landscape.

In agricultural districts, an agronomist's goal is to understand the cropping and pasture systems, the biophysical requirements of major species, and to be familiar with grazing and other cultivation practices. A sharp eye for crop and pasture performance can give clues on spatial variation in soil and landscape attributes.

Ecology

If the survey embraces specialist ecological outputs, then ensure the team has an experienced plant or animal ecologist. Few people these days are skilled in both pedology and ecology. Expertise in ecological management and land resource information is a precursor to dependable environmental management, conservation and pest management. These skills are also necessary to plan vegetation management that avoids land degradation or excessive grazing and depletes forest resources. The skills required to undertake a vegetation survey are similar to those used for land resource surveys (see *Chapter 8*).

Develop a good working knowledge of plant and animal species in each survey area and be familiar with local keys to taxa. Pay particular attention to indicator species (e.g. those indicating wetness, salinity, extremes of pH). Similarly, be familiar with characteristic patterns of vegetation in remotely sensed imagery. Understand land use history, and pay attention to fire, clearing and weeds. These all contribute to predictions.

Soil chemistry and physics

A solid grasp of soil chemistry and physics is a precondition for understanding the significance of soil morphological features and relating them to the basic processes underlying pedogenesis. Sound recommendations on soil use and management rest on these disciplines, and they also guide the development and application of pedotransfer functions. Finally, the knowledge they bring gives context for sampling and measurement of soil chemical and physical properties, both in the field and in the laboratory.

Specialised skills may be needed to address specific problems relating to water quality, parent material lithology, soil biology (e.g. the influence of soil-modifying organisms such as worms, termites, fungi), and interactions between vegetation and soil physicochemical properties. Members of the survey team need to be able to interpret chemical and physical data in terms of land productivity, management and use, soil genesis and behaviour.

Laboratory skills in soil chemistry and soil physics are essential for all surveys but they are usually required only on a part-time basis. Procedures for measuring soil chemical and physical properties are outlined in Rayment and Higginson (1992) and McKenzie et al. (2002) respectively. Hillel (2003) is a useful standard text, and so is Marshall et al. (1996). Peverill et al. (1999) provides a practical guide to the principles, concepts and factors of soil fertility testing in Australia.

Database management

Almost endless data are recorded during surveys, meaning that considerable skills in information management are needed for data input, verification, storage, manipulation, analysis and display. Regrettably, insufficient funds have been allocated to information management, and solid investment in this area is needed to make sure the survey data remain useful in the long term. Staff require working knowledge of database design, network operation, and methods for data entry, manipulation and presentation using various software packages (see *Chapter 25*).

In qualitative surveys, skills in information management are required mainly for designing data sets, accurate data entry, database management and reporting. Advanced skills in information management are critical for quantitative surveys. The field continues to develop rapidly.

Geographical Information Systems

Because of the sophistication and increasing ease-of-use of geographical information systems (GISs), it is difficult to be prescriptive about the skills required in this area. Staff members with a strong background and training in information technology and environmental sciences are ideal. They need a working knowledge of GIS hardware components (e.g. networked computers, field computers, global positioning systems, digitisers), operating systems, data structures, specialist software, Internet-based delivery and cartography.

GIS support staff for quantitative survey will require a working knowledge of terrain analysis, image analysis, and the capability to perform data analysis under supervision. Skills in landscape modelling are useful. Burrough and McDonnell (1998) and Longley et al. (2001) are standard references.

Statistics and data analysis

At some stage you will have to analyse data, and you might well require the help of a statistician. Such a person should have expertise in sampling, survey design, exploratory data analysis and geostatistics. You are required to appreciate the inherently statistical nature of your work (e.g. be familiar with *Chapter 21*) and use references such as Webster and Oliver (1990). In quantitative survey, the pedologist should be able to apply most of the methods outlined in other chapters (see *Chapters 20–24*), and in Webster and Oliver (1990, 2001) and de Gruijter et al. (2006).

Equipment

The type, amount and standard of equipment required for the different forms of survey depend on the exact nature of the operations to be undertaken. This will, in turn, control the effectiveness of physical effort and the rate at which the operations are conducted. Basic field and office equipment are outlined in Soil Survey Division Staff (1993) and Landon (1984). Table 15.2 provides a general list of equipment for land resource survey. (See *Chapter 16* for operation and maintenance).

Table 15.2 Office and field equipment for land resource survey

Office	
Furniture	Large desk-top area, well illuminated (preferably with natural light) Light table Computer desk(s) and ergonomic chair(s)
Machines	Photocopier, fax machine, scanner, telephones Laminator
Air photos	Stereoscopes – both pocket and mirror models are essential Pencils suitable for non-permanent marking of photographs (e.g. Omnichrom® or Chinagraph® pencils) Pens suitable for permanent marking of photographs Rescaling machine for plotting lines from photographs on to film base
Media	Tracing film and map-base film (e.g. Cronoflex®) Plotter paper Pencils suitable for drawing on map film (e.g. Omnichrom®)
Maps	For survey area Orthophoto maps Topographic maps (1:25 000 or 1:50 000) Geological maps (1:100 000 or 1:250 000) Existing maps of soils, land systems or land capability Satellite imagery
References	Australian Soil and Land Survey Handbook Series Textbooks, reports, theses Relevant reprints
Computing	Personal computers and standard office software, fast internet connection GIS software or network node Digitiser
Soil specimen preparation	Top-pan electronic balance: 0.1 g precision, 2–5 kg capacity, battery and AC power Air-dry soil racks in a protected, ventilated space Wide-mouth poly-jars for storing and transporting soil specimens

Field	
Vehicle	Suitable four-wheel-drive vehicle. Models with lifting rear doors are preferable for protection from rain. Models with rear storage area separate from cab have the advantage of minimising dust entry to cab. Storage area should be large enough to accommodate all gear, but not so large that it slides around and is difficult to reach Power winch and chains are recommended Roof-racks are a useful accessory Various plastic storage boxes and containers to compartmentalise the potential mess
Communication Navigation and orientation	Mobile phone, satellite phone or 2-way radio, depending on situation Maps, topographic and geological and solid cylindrical case Air photographs – 1:40 000 scale (or more detailed) contact colour prints with stereoscopic coverage Portable stereoscope Global Positioning System (GPS) receiver plus ancillary gear Pocket scale rulers for main topographic map scales to read map distances Compass and clinometer Circular plastic compass protractor preferably with magnetic offset capability for calculating compass bearings Hip chain Fibreglass tape (20–50 m) Flagging tape Surveyor's pegs/aluminium fence droppers/wire pegs
Digging tools	Jarrett auger with 100 and 75 mm heads, 1 m shaft and easily inserted 1 m extension shafts. Permanent depth markers down the shaft are useful. A built-in tamper to the shaft thread is also very useful Spades, including standard garden spade, narrower 'cottage spade' and long-handled square-ended shovel Crow bar, cut down to maximum length of 1.2 m ('spud bars') Gouge auger with suitable hammer is useful, but should be used with caution as considerable mixing of soil can occur Geologist's pick or crack/maul hammer and rock chisel Hoe pick, rabbit hoe or asparagus knife for cleaning vertical exposures Tree-limb pruner for cutting roots Chainsaw or large bush saw
Field kit	Field Handbook (McDonald et al. 1990) Soil profile tape (1–3 m) with nail or peg Long industrial plastic/canvas sheet (e.g. 0.4 x 4 m) with regular markings labelled at 0.1 m intervals (the spacing can be larger) for 0–3 m or greater. This is for laying out soil retrieved with an auger Munsell colour charts or equivalent (e.g. EarthColors) 250 mm wash bottle or spray bottle (water) Stout knife (e.g. scaling or asparagus knife) Spatula or putty knife for fine sampling Field pH test kit Chemical dimple or spot plate (pH testing) Pocket magnifier or lens (x 10 magnification) Pocket tape (2–3 m) – surveyor rod style is best Small (100 mm diameter) 2 mm sieve (pocket) for field texturing 100 mm bottle (1M HCl) with eye-dropper (keep in separate plastic container to avoid spillage) 100 mm clear plastic beakers/cups – aggregate stability tests Supplies of distilled water and tap water Cloth or paper towel(s) Bags (calico) with draw-strings, tags or labels for disturbed soil specimens

(Continued)

Table 15.2 (Continued)

Field	
	Specimen vials for aggregates or soil macrofauna Permanent marker pens, pencils, pencil sharpener, eraser, ballpoint pens Metal folder or clipboard for writing surface and data sheet protection Data recording sheets or cards Note book Ground sheet or tarpaulin with collapsible poles, ropes and pegs Small folding camp-stool Carrying case/pack for field kit
Bulk density	Coring equipment Core trimming and cleaning gear: knife, pruning shears, bottle brush Low friction or lubricant spray (e.g. WD40®) Metal sample cans with flush lids for transporting and oven-drying soil cores
Photography	Aluminium photographic box or waterproof pack Camera: high-resolution digital camera Flash unit Tripod (or monopod) White reflective board/sheet for pit floor CMYK colour card for digital cameras
Photo profile preparation	Straight-blade spade Trowel, spatula or stout knife Pick or hoe Root pruner Brushes Spray bottle Soil profile tape with large nail or peg Identification plate (metal with magnetic letters/numbers or plastic with marker pens)
Other kits	Comprehensive first aid kit Electrical repairs: batteries, rechargers, power boards, etc. Mechanical repairs: pliers, spanners, screw drivers, wire cutters, etc.
Laptop computer	Download GPS files and digital photos Initial database entries Environmental data (e.g. remote sensing, digital elevation model)
	Whatever else you have found effective

The survey organisation needs to be able to store and maintain equipment. It should hold a catalogue of equipment and keep track of its location, repairs and maintenance, and replacement. Supporting staff should be responsible for these tasks.

Information resources

Information for a survey includes digital data (data sets, maps, reports, field observations, remotely sensed data), printed products (maps, reports, aerial photographs) and expert knowledge. Allocate plenty of time and resources for acquisition, organisation and analysis of reference material. This makes field operations and data analysis more efficient.

Generally, printed reports, maps and images (air/satellite photographs) need a reference or catalogue system and adequate facilities for storage. Most traditional information relates to site and polygon data. Reference details of reports and maps are usually available through libraries or the relevant organisation that conducted the survey. Digital reference material should be listed as metadata attached to agency and national databases.

Most reports and maps can be obtained digitally and processed with standard GIS software. Web-based technology allows rapid access to an increasing amount of data and information. Most natural resource agencies have soil and land information systems and directories listing metadata and spatial data sets.

Scientific literature provides a valuable source of information. Private-industry reports and data are sometimes difficult to locate and are often inaccessible as a result of ownership rights, unless they are recorded in agency data sets.

You will need licenses and protocols for the use of software and data. These define rights of access, ownership and conditions of use. Make sure you understand the implications of laws relating to copyright, privacy and intellectual property. Guidelines on some of these matters are provided by ANZLIC (2006) and the National Land and Water Resource Audit (2006).

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Field operations

PJ Ryan, PR Wilson

Introduction

Putting people into the field is expensive, so plan thoroughly, minimise waste and maximise productivity. This chapter describes what is necessary – both in the field and in the office. It draws heavily on Beattie and Gunn (1988). In practice, each person should have several duties so that they get variety, breaks from tedium and relaxation from strenuous duties.

Health and safety

First and most important in planning field work are the health and safety of staff. Many aspects of fieldwork are potentially hazardous, and minor injury can seriously delay field work and jeopardise programs. Field workers need to be trained and prepared to recognise risky activities, and know how to avoid hazards. Project managers and field supervisors need to know what is required of them under the relevant federal, state and territory occupational health and safety legislation.

Comcare Australia administers occupational health and safety in the Commonwealth employment jurisdiction. Copies of their information should be distributed to staff (Comcare 2006). The information includes guidance for employers and others in meeting their duty-of-care obligations under the relevant Acts. Comcare Australia has also developed a set of *Approved Codes of Practice* that cover many listed regulations plus other aspects of health and safety.

The Australian Safety and Compensation Council (2006) coordinates national efforts to prevent death, injury and disease in the workplace. It maintains several databases: overcoming problems in occupational health and safety, hazardous substances, codes of practice and guidance notes.

Standards Australia (2006) lists and summarises many Australian standards for safe practices at work. The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA 2006) is the federal government agency responsible for protecting the health and safety of people, and guarding the environment, from the harmful effects of ionising and non-ionising radiation. The reference includes information on skin cancer, microwaves and radiation from mobile phones.

Individual states and territories have their own occupational health and safety legislation, regulations, codes of practice and standards that may affect operations during fieldwork. Most material is accessible through the Internet.

After reviewing and responding to regulatory requirements for occupational health and safety, review all work practices and pay particular attention to the following:

- use of machinery (e.g. backhoes, drill rigs, chainsaws, winches, jacks, electrical equipment)
- soil pits (e.g. depth and size limitations before formwork is required)

- injury (first-aid kits and training)
- potential risk of diseases, parasites, bites, stings, and allergic reactions, in particular:
 - mosquito-borne illnesses
 - soil fungi
 - snakes
 - spiders
- requirements for protective clothing, hats and footwear
- manual handling including lifting, digging and augering – back injuries as a result of poor augering technique, particularly when the operator is fatigued, is a significant risk in land resource survey
- breathing protection from dust and other particulate material
- skin care
- eye care
- working in remote locations
- communication (mobile and satellite phones, two-way radios)
- driving (all aspects of four-wheel driving, time limits, loads and long-distance driving)
- fire safety
- water safety including boating.

Pre-survey activities

After the project specifications are established (see *Chapter 14*), preliminary office work is needed before fieldwork can begin.

Background information

At the start of any project, background information should be sought. This includes spatial coverages (e.g. maps, air photographs), reports and scientific articles, and the knowledge of local experts. Determine the availability of this information during project design because it will affect the budget and the lead-time before routine survey can start. Pay particular attention to the following.

- Topographic maps for navigation and planning.
- Air photographs – acquire these from the relevant agency. Do this as early as possible in case new photography must be flown. Include provision for it in the budget and the timetable.
- Other items include geological maps, digital elevation models, climate surfaces, gamma radiometric images, electromagnetic induction and magnetic surveys, satellite imagery. Again, availability and supply should be resolved at the start of the project to allow time for any licensing or for contractors to do the work.
- Acquaint yourself with previous surveys and relevant scientific publications, and gather as much local information on land management (e.g. from district agronomists, foresters, farmers, catchment management agencies).

Survey planning and logistics

After compiling background information, formulate hypotheses about the spatial distribution of landscape attributes to be tested during the survey. Be as explicit as possible but vary your procedure according to the survey method (see *Chapters 3, 18, 22, 23*). Visit the field at this stage to understand the landscape. Such visits also help staff familiarise themselves with the region and the conditions likely to be encountered during the survey.

The main fieldwork involves implementation of the sampling plan (see *Chapters 18 and 20*). Do not leave those parts of the region with difficult access till the end of the survey; they might receive inadequate attention if time runs out. The number of sites to be examined during a survey depends on the survey specifications. Make sure realistic estimates of survey rate (e.g. number of sites examined daily) have been used in calculating the time allocated to fieldwork. The rate depends mainly on the amount or type of data to be recorded, the distance between sites, and ease of access. See *Chapter 14* for rates of fieldwork.

Schedules

Schedule fieldwork properly, and aim for a balance between field and office work. This ensures the project milestones are met on time and within budget. Critical-path network diagrams, or Gantt charts, can help planning by highlighting which activities have to be completed before others can begin. The main considerations for scheduling are as follows.

- Include regular periods in the office to allow recording and checking of data, updating draft maps, and preparing specimens for laboratory analysis. Quality improves when the time between fieldwork and checking in the office is minimised, because then missing or erroneous information can be more easily corrected from memory. Similarly, regular breaks from fieldwork counteract quality decline as a result of fatigue.
- Avoid seasons with unfavourable weather or periods when staff members have family commitments (e.g. school holidays).
- Allow adequate time for correlation of results between team members and between those senior staff responsible for regional correlation or quality control.
- Try to supply specimens to the laboratory in manageable batches at frequent intervals rather than in one large batch. Make sure analyses critical to the progress of the survey are submitted early (e.g. those that aid understanding of landscape processes).
- Plan routes to minimise travel time by ensuring more distant or inaccessible sites have to be visited only once.
- If possible, contact landowners in advance to seek permission to visit sites on their land.

Equipment

Reliable equipment saves time and effort.

- Ensure there is adequate transport capacity for staff members and equipment.
- Acquire necessary equipment prior to the start of operations. Allow time to select new equipment and for staff to become familiar with its operation.
- Check the availability of special equipment and the fieldwork schedule so that, if necessary, arrangements can be made to share equipment with other projects.
- Maintain equipment – this minimises delays from breakdowns and averts possible personal injury (in remote areas the results can be serious). Technically qualified staff should test and maintain equipment prior to field operations. Buy spare parts if necessary.
- To maximise productivity, plan well in advance, particularly when equipment has to be hired (e.g. excavators).

Technical and administrative routines

Inefficiencies can be minimised if well-specified technical and administrative routines are set in place.

- Prepare a list of equipment for each type of task and assign a staff member to be responsible for each item. This will minimise the time taken to load vehicles each day and ensure equipment is readily accessible – accidentally leaving equipment at the base wastes time.
- Outline the tasks to be carried out at each site. The procedures will depend on the list of attributes to be observed and measured (see *Selection of site and soil attributes*) and the specimens to be collected (see *Sampling for laboratory analysis*). If different attributes are to be observed at different sites, identify them for each type of site. While operations will probably need to be fine-tuned during the survey, establish them as early as possible to guarantee consistency throughout the survey and between field teams. Make sure that:
 - sites are accurately located
 - the characteristics of site and soil are observed and recorded
 - other measurements are made
 - specimens are collected
 - sites and soil profiles are classified according to the provisional map legend (conventional survey only)
 - store field data, soil and specimens securely – similarly, file field notes, refuel vehicles, recharge batteries (e.g. communication equipment, field computers, GPS receivers), and prepare air photographs and maps for the next day
 - clearly assign the above tasks to members of the team – if a team member is absent, ensure that other members of the team are aware of extra tasks that fall to them and who is responsible.

Information management

Information management includes all activities that allow us to record, assess, use and maintain information (see *Chapter 25*).

- Establish a database and geographical information system (GIS) for the data recorded prior to and during the project. Initially, it will help with interpretation of the landscape. As the project progresses, data will accrue and allow the understanding of the landscape to be improved in an iterative fashion. Design the database to fulfil two roles – data analysis and interpretation during the project, and long-term archiving of data into the survey group's database (and into regional and national systems) (see *Chapters 25 and 26*).
- Establish a clear and simple coding system for referring to the project and its sites.
- Code specimens for labelling and future reference. Include the organisation, project, site, horizon designation, depth and specimen number.

Selection of site and soil attributes

The objectives specified in the terms of reference (see *Chapter 14*) determine the important land qualities for land evaluation. These qualities in turn determine the site and soil attributes requiring measurement and estimation and hence the data to be recorded. The data may be used directly (e.g. to map surface-soil pH) – or indirectly to estimate other attributes through the use of pedotransfer functions (see *Chapter 22*).

The accumulated data have two other roles, to:

- 1 inform the surveyor about landscape processes and help him or her understand the spatial distribution of land and soil properties.
- 2 meet the needs – as yet unknown – of future users.

In the case of special-purpose surveys that are privately commissioned, the latter role may not be relevant. In many other cases, especially in publicly funded general-purpose surveys, the needs of future users must be considered. The least that can be done is to ensure that observations are made to recognised standards, recorded according to specifications, and stored in databases with proper information management (see *Chapter 25*). This will ensure information is accessible and readily understood by users.

Types of measurement

The kinds of measurement for land resource surveys (including minimum data sets) have been outlined (see *Chapter 17*). They range from auger holes, at which a few observations of soil morphology are made, to reference sites, at which full site and soil descriptions made, specimens collected and measurements taken. The kinds of sites also vary in accordance with the sampling scheme – they may range from rapid convenience samples, through purposively chosen representative sites, to randomly selected sites the positions of which have been predetermined by design (see *Chapters 18 and 20*). The relative numbers of each type of site needs to be planned in advance with reference to the survey intensity and method as specified in the terms of reference.

List attributes to be observed at each type of site, together with the methods to be used. It is not unreasonable for the same attributes to be measured by different methods at different types of sites. For example, water-holding capacity might be estimated at most sites from easily measured attributes and pedotransfer functions, whereas at reference sites specimens might be taken for laboratory determination. The laboratory measurements from the reference sites can then be used for local calibration of the pedotransfer function.

Databases will always have large portions of ‘censored’ data. This is because the depth of characterisation is limited by the method of observation (e.g. soil augers or backhoe pits are often restricted to 1–2 m) or survey purpose (e.g. many agriculturally focused surveys were concerned only with the first metre). So, record data limits and the reason (e.g. standard procedure, lack of time, limit of equipment, coarse fragments).

Data collection standards

State the data collection standards for site and soil observations at the survey specification stage (see *Chapter 14*), with explicit reference to the type of mapping (see *Chapter 3*) and sampling strategy (see *Chapters 18 and 20*). The primary standard for coding field attributes described in land resource surveys in Australia is McDonald et al. (1990). Standards for other attributes can be found in the following references:

- soil classification – Isbell (2002)
- soil physical properties – McKenzie et al. (2002)
- soil chemical properties – Rayment and Higginson (1992) and Rayment et al. (in press).

Standard methods facilitate comparison between individual surveys and contribute to inventories of soil and land attributes for larger regions. Specification of methods used in accompanying metadata is also easier. Supplementary procedures can also be found in:

- New South Wales Soil Data System – Abraham and Abraham (1990)
- regolith and terrain – Pain et al. (2000)
- land use – Chapter 9.

Data sheets, cards and electronic entry

Most agencies and companies use standard sheets for field data that should be used if appropriate. Otherwise use the field sheet in McDonald et al. (1990). Field data capture and entry is

a limiting step in land resource survey (see *Chapter 17*). The soil–landscape mapping group in New South Wales has pioneered the use of mark-sensed cards for soil data. These machine-readable cards can be designed for specific surveys.

There have been many attempts to use portable field computers for direct entry of site and soil attributes. Field conditions in land resource survey are tough for electronic equipment because of moisture, extremes of temperature, rough terrain, bright light, dust and mud. Few designs have survived, though the evident merits of computers for data entry and recording, and in readily integrating other information, such as location (via global positioning system receivers) and digital photographs, means that robust systems will almost certainly appear soon.

Georeferencing and navigation

Many methods are available for identifying the location of a point. The ideal is to navigate to an observation point, accurately georeference it, and store its coordinates (along with an estimate of its uncertainty). The following describes some basic concepts for georeferencing and equipment. See Maling (1973) and information from organisations listed below.

Spatial coordinates

A unique location in three-dimensional space requires determination of three variables (x , y and z) and a frame of reference (the *datum*). The most commonly used geospatial datums rely on a geometric model of the earth (usually a spheroid or ellipsoid) positioned either geocentrically (origin at the centre of the earth) or to best fit a particular region of interest.

The World Geodetic System 1984 (WGS84) datum, which is based on the WGS84 ellipsoid, is a geocentric datum. This datum is widely used because it is the default for satellite-based positioning systems such as the GPS.

Historically, Australia has used the Australian Geodetic Datum (AGD) for mapping purposes. This datum is based on the Australian National Spheroid (ANS) and is not geocentric. Two widely used versions of this datum were AGD66 and AGD84. More recently, the standard Australian datum was updated to the Geocentric Datum of Australia (GDA), the current version of which is known as GDA94. This datum is based on the GRS80 spheroid and is geocentric. There is a shift of about 200 m between coordinates measured against AGD to those measured against GDA.

Projections

Coordinates measured directly against a datum are generally reported as a latitude and a longitude. The units of measure are degrees, minutes and seconds (often decimal degrees). To transfer these angular coordinates to a Cartesian (two-dimensional) coordinate system, they need to be projected.

There are many different projections. Most topographic maps in Australia use a Transverse Mercator projection. This is referred to as the Map Grid of Australia (MGA) where it is based on the GDA94 datum. Older maps use the Australian Map Grid which is based on the AGD 66 and AGD 84 datums.

Both the MGA94 and AMG66/84 projections are forms of the Universal Transverse Mercator (UTM) projection and this is used by many countries. To minimise distortion in the projection, the Earth's surface is divided into zones of 6°, each having a local Cartesian origin. Australia is covered by Zones 49 to 56. Within a zone, location can be specified by a six-figure Easting (x coordinate) and a seven-figure Northing (y coordinate) in metres. Locating a position accurately using a UTM projection requires three values: the Zone, Easting and Northing.

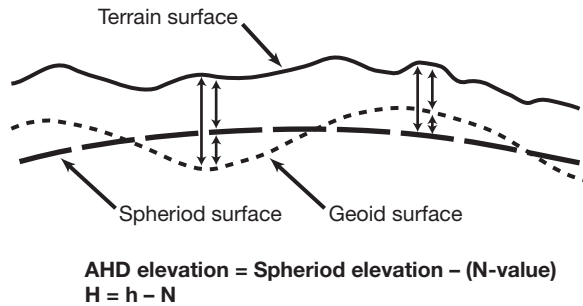


Figure 16.1 Calculation of Australia Height Datum (AHD) elevation from spheroid elevation and geoid N-value.

Always check that a correct number of significant figures has been used to represent the coordinates accurately.

Geoids and elevation

Elevations have been traditionally measured with respect to a datum associated with mean sea-level. In Australia, this datum is known as the Australian Height Datum (AHD). In reality, this particular datum is a gravitational equipotential surface known as the geoid.

The advent of satellite positioning systems allows elevation to be estimated as a distance above the reference ellipsoid. The reference ellipsoid is a representation of the geoid but rarely coincides with it. Thus, conversion of an elevation determined using a system such as GPS, to the AHD requires calculation of the difference (known as an *N*-value) (Figure 16.1). The current method for calculating *N*-values in Australia is AUSGeoid98. This consists of a 2×2 minute grid (about 3.6 km^2) of geoid–ellipsoid separations (*N*-values) relative to the GDA94.

Various programs are available (commercial and freeware) that readily convert geographic to cartesian coordinates, or convert between datums or projections. You can also estimate an *N*-value from the AUSGeoid98 data files using the Windows Interpolation software (WINTER) (Geoscience Australia 2006). These programs run on personal and palm-top computers, and so can be used in the field or office.

In summary:

- use GDA94 as the geographic datum unless the client has specified otherwise
- use the relevant UTM cartographic projection based on the chosen geographical datum
- know and record the UTM zone within which you are working
- if you are using satellite-based positioning to measure elevation, determine the *N*-value to convert to AHD elevations.

Satellite positioning systems

Satellite-based positioning systems, such as the GPS, have revolutionised our ability to determine locations accurately. There are significant implications for fieldwork, especially in quantitative survey where accurate registration of field and remotely observed observations is essential. The technology behind these systems is not described here (but see Hofmann-Wellenhof et al. 1997; McElroy 1998). It is changing rapidly, so consult current sources or commercial websites to obtain the latest information (SNAP 2006). However, an appreciation of the principles behind the main classes of GPS unit is required, and the following is adapted from Rizos (2001).

Main classes of commercial GPS units

Stand-alone navigation receivers

These are the cheapest GPS units (typically a few hundred dollars) that combine an antenna, receiver, operator interface, data storage system and batteries. The receivers have few options for configuration. They are the result of rapid innovation in the mass market for single-point positioning units, and their widespread use has led to reduced cost, size and power consumption. Features include:

- single-frequency (L1 signal)
- a single-point positioning algorithm (see *Single-point positioning*), based on the processing of pseudorange data
- horizontal accuracies of 5 m to 10 m (95% confidence), and vertical accuracies of 2 to 5 m.

Differential single-point processing receivers

These units typically cost several hundred to several thousand dollars for the receiver and operator interface, with additional costs for the differential GPS (DGPS) message receiver and service subscription. Features include:

- single frequency (L1 signal)
- use of a single-point positioning algorithm, based on the processing of differentially corrected pseudo-range data (see *Differential processing*)
- horizontal accuracies of 1 m to 5 m (95% confidence), and vertical accuracies 0.5 m to 2 m
- accompanying software for the GPS unit and personal computer allows management of operation mode, collection of feature attributes, specification of waypoints, differential processing, datum and projection management, and data transfer
- dependence on the availability of DGPS services.

Differential carrier phase-based receivers

These units cost several thousand to a few tens of thousands of dollars for the receiver and operator interface, with additional costs for the base-station receiver or service subscription or both. These specialist receivers and techniques are appropriate for precise surveying and machine guidance or control applications.

Features include:

- single frequency (L1 signal) or dual frequency (L1 and L2 signals)
- carrier-phase processing algorithm
- capable of horizontal accuracies of 0.02 m to 0.5 m (95% confidence), and vertical accuracies of 0.01 m to 0.02 m
- software for the GPS unit and personal computer enable management of operation mode, collection of feature attributes, specification of waypoints, differential processing, datum and projection management, and data transfer.

Main methods of GPS survey

Single-point positioning

A mathematical solution of geoposition by a GPS unit using single-point positioning (SPP) is called an *epoch*. Precision and accuracy of an estimated geoposition are improved if multiple epochs are integrated. The time interval between epochs is programmable on most GPS units, but the ability to integrate varying numbers of epochs is found mostly on differential units.

Part of this results from the need to keep the GPS antenna static and provide power for periods from 5 minutes to 24 hours. The minimum static time required is calculated as the number of epochs multiplied by the time interval. For example, choosing a 30 s interval and 50 epoch integration will require the GPS antenna to remain static for at least 25 minutes. This is not feasible for a handheld antenna without some means of stabilisation such as a monopod or tripod.

Acquiring single epoch-by-epoch solutions for consecutive intervals while the GPS antenna is static or in motion for a set period of time is called *kinematic* or *stream* mode (in contrast to the *static* or *fast-static* mode above. Kinematic mode is used for tracking vehicles in precision agriculture and for positioning irregular transects.

Differential processing

Differential processing (DGPS) was developed to overcome the selective availability (SA) 'error' programmed by the United States Government into the GPS satellite signal for non-military use up to May 2001. By having a second GPS unit recording epochs at an accurately known location (reference or base station) at the same time as the first GPS, it is possible to differentially process the two GPS files epoch-by-epoch and eliminate the SA. The SA was turned off in 2001, but Rizos and Satirapod (2001) and Satirapod et al. (2001) have shown that differential processing still provides significant improvement over single-point processing, especially when the averaging period increases to 60 minutes.

Base stations can be set up specifically for a survey, but they require a second GPS unit with differential capability. Such a base station is best placed at an accurately known point to obtain the optimum precision and accuracy in differential processing. This may require use of local trigonometric stations or survey points to tie the base into the geodetic network.

If less accuracy (<0.1 m) is acceptable, then temporary base stations can be established at convenient locations and allowed to run during work hours or for longer periods. The average geoposition for all recorded epochs of these base stations can then be used as the known location. Following the turning off of SA, this latter procedure has become more acceptable.

There are some important considerations for locating any GPS base station:

- clear view of the sky optimises the antenna's ability to see the GPS satellite constellation without interference from terrain, trees or buildings
- the site should be secure, with equipment protected from vandalism and the elements because equipment worth several thousand dollars will be left in the open for at least several hours
- there needs to be an adequate power supply to allow the GPS unit to run and log data for the time required
- the GPS base station unit should have the capacity to store the amount of data collected over the time required.

An alternative to setting up your own base station is to use base station services offered by various organisations. These services supply a data stream for you to process differentially against files from your own GPS unit.

Real-time differential GPS (RTDGPS)

For real-time differential GPS (RTDGPS), a GPS base station can be extended to transmit the reference signal via ultra-high frequency (UHF) or very high frequency (VHF) to a rover unit that has a radio-frequency receiver. This allows real-time differential processing as long as the rover can receive the signal.

There are organisations that broadcast GPS base station data via frequency modulation (FM) radio networks or satellite. These coded radio signals can be accessed in the field with a special radio-frequency transceiver and allow real-time differential processing of any acquired GPS record. Most broadcast GPS services charge annual subscription fees and require special receivers.

Limitations of satellite positioning in field survey

Satellite positioning is valuable for field survey, but there are limitations.

- anything that interferes with the satellite signal before it reaches the GPS antenna will cause loss of accuracy – trees are major obstacles and certain atmospheric conditions can also cause problems
- terrain with high relief (e.g. cliffs) or nearby buildings will block access to satellite signals
- reflective surfaces can bounce the satellite signal to the antenna and cause multipathing – this degrades positional accuracy
- satellites change their positions, so there are times when the satellite constellation is poorly configured (too few visible satellites or too many at low azimuths) to allow an accurate geoposition.

These limitations mean that there will be certain sites and times when accurate geopositioning is not possible. Some of these can be overcome with planning. Differential GPS units usually have planning software to calculate the satellite constellations for up to 60 days ahead and so avoid days or parts of days with poor constellations. In forests, be prepared to average a larger number of epochs or use offset measurements.

In summary:

- Class 1 GPS units (SPP) are good for general navigation and some reconnaissance survey where accuracies of ~20 m are acceptable. Make sure each field team has at least one such unit.
- GPS units with differential processing should be used for quantitative survey applications requiring accurate sampling positions with an accuracy of <5 m.
- Plan ahead for field trips where GPS is to be used, and decide what landscape features you want to locate, the accuracies you require, additional features you need to record for each location, strategies to use if under trees, and times you want to avoid because of poor constellations.
- Record some measure of location uncertainty (e.g. certain GPS units will output differential root mean square, DRMS, for processed locations or Position Dilution of Precision, PDOP, to indicate uncertainty).
- Archive all GPS unprocessed rover and base station files.
- Use of GPS increases the amount of electronic and computer equipment to be transported – be prepared with extra fuses, batteries, battery chargers, cable and toolkit.
- GPS technology is rapidly changing – plan to replace equipment within 5 years.

Air photographs

Air photographs (see *Chapter 10*) are commonly used as the mapping base for soil and land survey. The value of aerial photographs in the field lies in the ease with which you can find out where you are. For maximum benefit coverage should be as recent as possible.

At the scales used for intense soil survey, you need to know where you are to within a few metres. Useful features may be the intersections of fence lines, roads, tracks, identifiable trees,

bushes, farm buildings, rock outcrops, and other features readily identifiable on the photographs.

To avoid cluttering up the image surface of the air photograph, use a pin to prick site locations, and mark details next to the pin-holes on the back of the photograph. Advantage can be taken of the two-thirds overlap of adjacent prints to record such details on alternate prints, so retaining a clean set of prints with one-third overlap. A pocket magnifier is useful for observing local ground features on the photographs.

Remotely sensed images

Increasingly, high-resolution panchromatic and multispectral images with pixel sizes in the 1 m to 10 m range have become available for large parts of Australia (see *Chapters 11* and *12*). Examples are the SPOT and IKONOS products that can be digitally rectified to a required map projection and used for navigation in either hardcopy or digital forms. Even the coarser resolution Landsat-TM scenes can be useful for identifying surface features and general navigation. The combination of rectified digital satellite images with other digital data (e.g. cadastre, infrastructure, drainage, coastlines) can provide extra useful information for navigation.

Maps

You need maps for planning and navigation. Obtain copies of the finest resolution topographical maps covering your region. Coarser scale maps are also useful to cover the full extent of the region on one sheet of paper. For scales finer than 1:50 000, topographic maps are produced and marketed by the relevant state or territory agency. For maps at scales of 1:50 000 and coarser, Geoscience Australia is the main provider. Hardcopy and digital maps can be purchased in most states and territories. Other maps, such as those of geology and cadastres, might also be useful for navigation. Remember to:

- laminate field maps to protect them and ensure a long life
- check rights of way for access
- plan inspection points along accessible routes so as to intersect major geological boundaries and cover all variation visible on the aerial photographs
- for significant areas that are publicly inaccessible, locate the most likely houses to call at to seek permission to enter
- obtain permits for access and sampling of lands under particular tenure (e.g. National Parks, Nature Reserves, State Forests, Aboriginal land).

Site observations

The procedure for selecting sites depends on the survey method. For information on measurement and sampling, see *Chapters 17, 18* and *20*.

Site variation

Characterisation of the variation at sites has generally been neglected, even though short-range spatial variation of soil is usually substantial. Adoption of the soil individual as an entity for sampling is a first step. In conventional land resource survey, measurements at individual sites are rarely replicated. However, for certain purposes (e.g. monitoring), it may be necessary to estimate the mean and variance for the soil individual so that comparisons can be made with later times (e.g. in paired site studies or experimental sites, McKenzie et al. 2000). McKenzie et al. (2002) specify procedures for determining soil carbon, but the techniques are applicable to high-intensity surveys of other attributes.

Field site selection

On arrival at a chosen site, first assess whether it is acceptable. There can be valid reasons to reject a site even in quantitative surveys (e.g. recent roadworks or coincidence with a dam). Have a list of criteria for accepting or rejecting sites *prior* to field operations, and document all reasons for rejecting sites.

Refer to your plan for the type of measurement at each site. Be prepared to spend whatever time is necessary to observe, measure and sample the properties as set out in the plan. At other sites, such as those for checking map-unit boundaries, such detail is not required – a location and classification may be sufficient. Record observation intensity and survey purpose in the metadata because they affect the way data should be used in statistical analyses or at a later time by third parties.

Soil observations

Record the attributes of the site first. Then record the soil.

Freshly dug pit

This is the preferred method for soil characterisation. If you need to sample or observe the soil below the bottom of the pit, you can do so with a hand auger. Fill the pit after sampling unless there are good reasons to keep it open.

Advantages

- vertical and lateral variation is easily observed
- you avoid compacting specimens
- horizons are easy to sample with little or no contamination of specimens
- exposures are easy to photograph
- undisturbed specimens can be collected for physical measurements.

Disadvantages

- pits can be costly if contractors have to be engaged, or organisations may have to cover the capital cost of a backhoe or excavator
- there is a substantial labour requirement when pits are dug by hand
- some land is too steep, and in wetlands a pit soon fills with water.

Cores of 100 mm to 150 mm diameter (Proline core)

Undisturbed cores with a diameter of 100 mm to 150 mm or larger can be removed with a Proline drill.

Advantages

- Proline drills can sample most soils to depths greater than 10 m or to hard rock
- field costs are reduced by transporting cores to a regional centre, where the soil can be sampled and described
- little contamination of specimens
- one can collect small, undisturbed specimens for physical measurements
- there may be some advantage over pits where the watertable is close to the surface.

Disadvantages

- lateral variation is not easy to observe
- large, undisturbed specimens cannot be collected
- there may be compaction
- some features of soil structure cannot be observed
- restricted access for vehicles
- coarse fragments can cause problems
- organisations face the large capital-cost of a drill rig.

Cores of 50 mm to 75 mm diameter (thin-wall sampling tube)

Cores of 50 mm to 75 mm diameter are obtained with a thin-wall sampling tube, which is pushed into the ground with a hydraulic ram or jackhammer. It will not penetrate hard soil, although deeper sampling can be completed with a hand auger.

Advantages

- quick and easy for sampling
- large numbers of profiles can be sampled
- little contamination.

Disadvantages

- lateral variation cannot be observed easily
- some aspects of soil structure cannot be observed – not as good as Proline cores
- restricted access for vehicles
- coarse fragments, hard segregations, and hard or wet soils can cause problems
- in some cases, not enough soil material is gathered in a core for an adequate specimen
- undisturbed specimens for physical measurements cannot be collected.

Existing exposures

Sampling from existing exposures (e.g. road cuts, gully banks) is undesirable because:

- the topsoil is often disturbed, absent, or overlaid with other material
- you cannot tell how representative the exposures are.

However, exposures do reveal lateral variation in soil and regolith. If you do choose to record such exposure, then ensure that there has not been addition to, or removal of, surface materials. Cut back the exposure to material that has not been disturbed mechanically. Do not treat such sites as soil reference sites.

Advantages

- exposures are often accessible to depths greater than you could reach with the usual field equipment
- displays lateral variation over one or more landform elements not visible by any other means
- may reveal stratigraphic relationships and variation with landform.

Disadvantages

- exposures are biased samples of soil and regolith because roads and quarries occupy particular parts of the landscape for a reason (e.g. avoidance of wet areas)

- soil properties change because of exposure (e.g. leaching, dessication, oxidation) and possible amendments (e.g. hydromulching)
- surface layers are often disturbed or scalped in road construction or removed by erosion
- examination may damage the roadside batter and cause erosion.

Hand auger and small pit

A hand auger is used in conjunction with a pit. This small pit should expose the A horizons and at least the upper part of the B horizon. Obtain specimens from these horizons from the pit and deeper layers with the auger.

Advantages

- quick and efficient in moist, light to medium-textured soils with small amounts of gravel
- steep slopes and access are not a problem
- minimal requirements for equipment.

Disadvantages

- augering is labour intensive and time consuming in deep or strong soils
- undisturbed specimens cannot be collected without specialised equipment
- lateral variation cannot be observed
- soil structure cannot be described reliably
- coarse fragments, hard segregations, sands, and hard or wet soils can cause problems.

Soil pits

A freshly excavated, full-size pit is the preferred means for describing, measuring and sampling soil profiles, so further guidelines have been presented for these.

The pit should be large enough when dug for comfortable working at a face. It should be 0.6 m to 0.9 m wide and deep enough to record what is regarded as significant for the purpose of the survey. Its length will be determined by the depth. Orientation can be affected by several factors:

- local site factors such as position of trees, rocks, and gilgai
- slope – it is easier to excavate upslope with the length of the pit oriented in the direction of maximum slope
- optimal lighting.

When excavating pits by hand, it is neither necessary nor appropriate to dig to a uniform depth. Depending on final depth, one or more steps (about 0.3 m tread with 0.3 m risers) should be left (Figure 16.2). *Pits deeper than 1.5 m require bracing to meet occupational health and safety requirements.* During excavation, protect the soil surface above the face to be described and sampled by laying a piece of heavy canvas or plastic sheet at that end of the pit. Place it to one side when you begin to collect specimens and use it to receive individual specimens as they are removed, before packing them for transport to the laboratory. Backhoes and small excavators are useful, but some manual excavation may still be required (Figure 16.3).

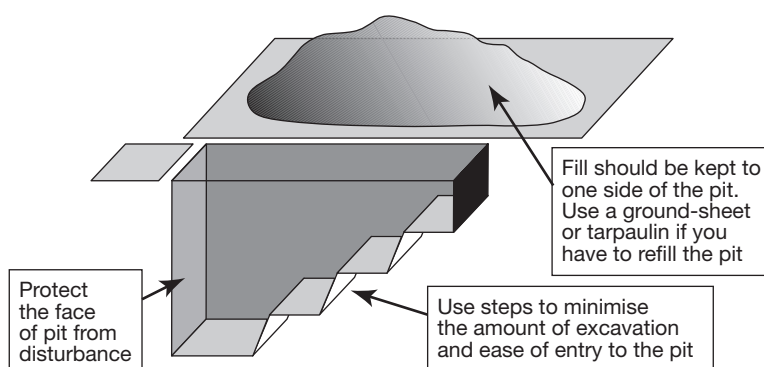


Figure 16.2 An idealised representation of a manually dug soil pit.

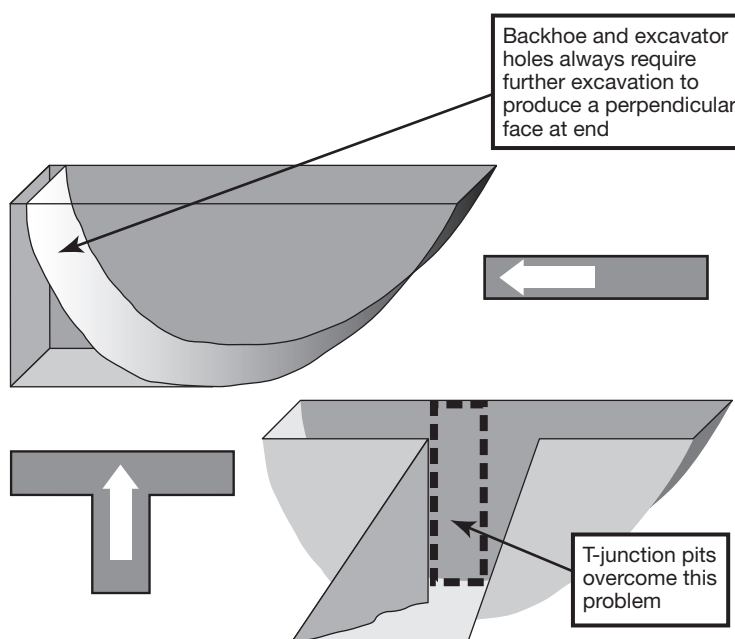


Figure 16.3 Design and preparation of mechanically dug soil pits.

Soil core guidelines

Modern mechanised equipment for continuous coring, such as the Proline or Geoprobe, allows quick and easy collection of cores. The morphology of cores can be described in the office or laboratory, but site descriptions need to be completed in the field. Ensure you register the depth of cores below the first section to take account of any loss of continuity between successive sections (up to 0.05 m of core may be lost between successive sections when using the Proline). Compression can be significant when wet soils are sampled with corers of small diameter.

As noted above, single small-diameter cores do not reveal lateral changes in soil that are often visible within the dimensions of a pit. The collection of multiple cores can overcome this deficiency to some extent.

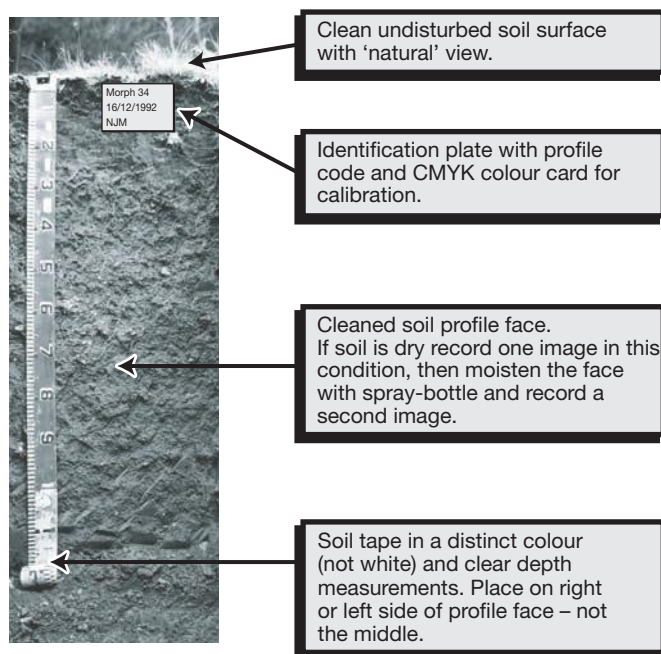


Figure 16.4 A well-prepared soil profile. Note the clear land surface (no spoil heaps or equipment disrupting the natural view, visible identification plate, soil tape placed to one side, freshly prepared profile face, card for colour calibration).

Photography of landscape, site and profile

Images of sites and their associated soil profiles are valuable for extension, education and other purposes. Take photographs of the local landscape, land uses, rock outcrops, site features (e.g. erosion, rock outcrop, vegetation), and soil features such as diagnostic horizons, concretions and mottles. The following guidelines for obtaining good photographs are based partly on MacNish (1984).

Profile preparation and lighting

The orientation of soil pits is important for good photographs. Natural sunlight can produce sharp contrasts of shade and light that obscure subtle variation in the profile, though full sunlight without shadows can be satisfactory. Light cloudy conditions offer uniform lighting, which might be best. Orient the pit so that the face to be photographed will be illuminated by the sun at the time. Flash or flood lighting produces an evenly lit photograph but the resulting colours can be unnatural. When pits are deep the bottom of the face might receive less light. A reflective screen placed along the base of the pit ensures even lighting across the base of the profile. A sun-screen made from black cotton provides good shade when the pit cannot be aligned as preferred.

The face of the soil profile should be picked back to expose the natural ped faces where present. A non-reflective black or coloured tape with clear depth markings should always be used (Figure 16.4). Soil profiles are best photographed when moist, so they match morphological descriptions – spray water on dry profiles from a bottle.

Obtaining the image

Use a high quality digital camera with images of at least 5 megapixels. The in-built automatic light metering is usually adequate, but, to be sure, take multiple images that span a

range of apertures. Photographing soil profiles is difficult, so the ability to view and assess a digital image quickly is useful. Digital images can be modified and processed to overcome various exposure, contrast or saturation problems. To this end it is useful to have a standard CYMK colour card positioned midway down the profile to allow for any image processing.

The video options in digital cameras are useful too. Video offers any easy means for recording site features; for instance, panoramas can be used to recall individual sites once back at the office.

Sampling for laboratory analysis

Follow the guidelines on specimen collection (see *Chapter 17*). In pits, proceed by progressive excavation of a vertical rectangular section, subsectioned by depth intervals or soil horizons or both. To obtain sufficient specimens from thin layers, it may be necessary to collect from a larger cross-sectional area than for the rest of the profile. Conversely, this may result in too large a specimen if depth intervals are increased deeper in the profile. Do not solve this problem by reducing the cross-sectional area of the section. To avoid bias, the soil profile should be excavated to a uniform cross-section. You can reduce the size of a specimen before packing by mixing and quartering the bulk specimen to produce one that is representative. Avoid contamination by incomplete removal of overlying material or by failure of side or back walls of the lengthening collection channel. In most cases, it is best to start from the base of the profile to minimise contamination.

There are two main ways of laying out auger borings:

- place a clean plastic sheet next to the sampling site and put the soil from auger borings in rows from each 0.3 m layer of profile, or
- place a long plastic sheet (about 0.4 m × 5 m) with regular markings every 0.1 m and place on it the soil from the auger in an artificial profile.

Specimens can then be collected from the horizons of the profile according to the intervals specified in *Chapter 17*. Withdraw the auger with as little disturbance as possible to the sides of the hole to avoid contaminating specimens with material from above. Collect specimens from the upper horizons from small pits dug with a spade. With specimens of gravelly horizons, include the gravel so that you can determine the content by weight and check estimates of volume. Make sure the auger has clear depth markings.

Bulking

An optional, but recommended, procedure to provide a precise estimate of nutrient concentrations is to collect at least four specimens (usually cores) from at least the upper 0.3 m to produce a bulked specimen. These cores can be collected on a grid pattern from a 1 m to 2 m square centred on the main observation point. Ideally the number of cores is taken from a curve of variance against sample size for the soil property of interest – it will normally be more than 4 and 16 is often desirable.

Bulked specimens from the upper 0.3 m can be conveniently collected using a manual soil corer. Alternatively, use a mechanical corer. At least three standard depths (i.e. 0–0.1 m, 0.1–0.2 m, and 0.2–0.3 m) should be sampled and bulked unless major horizon boundaries occur. Guidelines for bulking (composite sampling) are described in McKenzie et al. (2002) and de Gruijter et al. (2006).

Rock and regolith specimens

These *Guidelines* focus on soil and near-surface materials. Taylor and Eggleton (2001) guide practitioners on methods for studying regolith. Some rocks and regolith materials contain

appreciable stores of soluble salts (Dimmock et al. 1974; Gunn and Richardson 1979), available nutrients and water (Childs and Flint 1990; Ugolini et al. 1996). Although it is not usually possible to investigate the chemical properties of material deeper than 5 m during routine land resource surveys, some information can be obtained from specimens from a few sites by deep coring. Do not collect specimens from outcrops and scarps because they will not normally represent the regolith from which the soil has formed.

Water specimens

Specimens may be collected from surface waters such as streams, lakes, ponds and farm dams or from groundwater where a watertable has been intersected by excavation, drilling or augering. Guidelines are provided by ARMCANZ/ANZECC (2000). Rapid monitoring of streams for pH and electrical conductivity can be effective for salinity investigations because mobilisation of salts is often restricted to particular landscape types.

Specimen size, containers, labelling and identification

Devise your system for labelling specimens prior to fieldwork. McKenzie and Cresswell (2002) provide a guide on the collection and transport of specimens. Disturbed specimens that will be air-dried before analysis are best dried before final packing. This reduces weight and possible deterioration if more than a day or so will elapse before the specimens are unpacked. When specimens are transported in field-moist condition, minimise the time between packing and laboratory processing. This is crucial for properties measured on field-moist soil, such as nitrate or nitrite content. Rapid drying, refrigeration or freezing may be required for specimens that deteriorate rapidly (e.g. pyritic sediments).

The orientation of the specimen in the soil profile needs to be known for some analyses. Continuous cores offer little danger of confusion if they are forwarded intact and marked with an arrow indicating upwards. Pack cores in plastic piping – drainage-grade piping can be split lengthways and secured with hose clips. Fill gaps with inert plastic foam or cotton wool. Internal and external labelling is necessary, and keep track of depth registration with successive cores. Orientation can be lost when cores are sectioned in the field or small, undisturbed specimens are collected in boxes fitted over monolith sections. Record orientation when you collect the specimens or when you cut them – do not wait until an entire core or profile has been sectioned.

Refer to McKenzie and Cresswell (2002) for guidelines on handling and transport of undisturbed specimens for measurement of hydraulic conductivity and water retention. For routine determinations of particle size, cation exchange capacity (CEC), exchangeable cations, electrical conductivity (EC), pH, organic carbon, and nitrogen (N), phosphorus (P) and potassium (K), take specimens large enough for immediate analytic needs with an allowance for a small surplus and archiving. Each specimen should contain between 1.5 kg and 2 kg of material. Of this, 0.5 kg is processed for routine analysis and the remainder is retained for future use. The percentage of coarse fragments is determined from the initial 0.5 kg specimen. A larger specimen will be required in very gravelly soils to ensure a representative sample – see McKenzie and Cresswell (2002) for guidelines on volumes.

Collect specimens in light canvas or calico bags. Heavy-gauge plastic bags can also be used. Cloth bags are preferable, but plastic bags may be used if the specimens can be laid out to dry within a few hours. Otherwise there might be undesirable effects of incubation. Label the outsides of the bags and include a small, water-resistant tag inside them. Make sure the bags are sealed securely.

Specimen size may range up to many kilograms for some bulk density or particle size determinations on materials with coarse pedality or large and abundant coarse fragments. The very

coarse fraction of stony soils can be estimated in the field to reduce the size of specimens for transport to the laboratory by:

- visual rating with charts (McDonald et al. 1990)
- measurement and size grading in the field (O'Connell et al. 2000)
- sieving and weighing (Vincent and Chadwick 1994).

Post-field procedures

Once soil specimens have been returned from the field, immediately:

- make an inventory of specimens received at the office based on specimen labels and cross-check this against survey field sheets
- investigate any discrepancies between specimens sampled in the field and those received at the office
- pre-treat specimens if you can at the office before you send them to the laboratory or other central site.

Pre-treatment will vary with survey specification, office location and available facilities. Some of the most common practices are listed below. Further information is presented in Rayment and Higginson (1992) and McKenzie et al. (2002).

Air-drying, grinding, sieving and splitting

All disturbed specimens of soil should be air-dried unless special conditions have been encountered (e.g. anaerobic or acid sulfate soils) or special sampling procedures specified (e.g. field-moist soil for incubation or mineralisation). The aim of air-drying soil is to reduce the water content and prevent chemical and biological reactions prior to analysis. Cloth specimen bags are good for rapid and convenient air-drying. Plastic bags can cause problems when specimens are saturated or very wet.

Dry specimens in large ovens and follow the directions in McKenzie and Cresswell (2002). If you do not have ovens, then dry the specimens in air. Protect them from direct sunlight, rain, condensation, dust and vermin, and ensure there is good ventilation. Place specimens on a flat, clean surface that is above ground. Racks of metal-mesh trays maximise ventilation and minimise space. Specimens in cloth bags can remain sealed but those in plastic bags will have to be opened, and this creates a risk of contamination. Most specimens require only 5 to 7 days of air-drying but wet specimens might need more and should be separated from the rest. Once air-dried, specimens can be packaged for transport to the laboratory or processed on-site.

Soils with strong consistence can be difficult to grind after drying so break down specimens before or during air-drying. Again, sealed cloth bags are useful because a mallet can be used on the bagged specimen. Otherwise, a large mortar and pestle are recommended. Again, refer to McKenzie and Cresswell (2002) for guidelines on grinding, sieving, subsampling and archiving.

Archiving

At present, the responsibility for soil archiving rests with the relevant survey agency. Experience has shown that, with a few notable exceptions, archives established by small groups are neglected despite their long-term value. Therefore, consider lodging soil and related data with the CSIRO National Soil Archive at CSIRO Land and Water in Canberra. The economies of scale associated with this archive should ensure that a comprehensive collection can be assembled and maintained. Specimens from the archive are readily available to all collaborating agencies.

Hydrosols and Organosols

Hydrosols sampled in a saturated state are difficult to handle. They can be contaminated with water from elsewhere in the profile. Specimens take long to dry, and biological activity and chemical reactions can continue during drying and that affect laboratory analysis. Pyritic specimens require immediate refrigeration in air-tight containers.

The physical and chemical properties of acid sulfate soils (e.g. Sulfidic Hydrosols) can change dramatically when the soils are exposed to oxygen through disturbance or drainage. Oxidation generates sulfuric acid and various forms of iron. The acid in turn attacks the soil clay, releasing aluminium into the soil solution and this dramatically changes the physical structure of clayey sediments from impermeable gels to highly permeable, strongly structured soils. These then shrink irreversibly. Dent (1986) describes the process in detail. These soils require special sampling and analysis (Ahern et al. 2004; Rayment et al. in press).

Organosols, like Hydrosols, require specialised sampling procedures. These soils are prone to rapid oxidation if sampled in a reduced condition. However, rapid drying of saturated specimens is often not practical (very efficient ovens are needed). Specimens may need immediate refrigeration. Volume change can be substantial (see *Chapter 17*).

Post-fieldwork

Checking the many data recorded during field work is tedious but has to be done. There are two components: checking the field sheets, and checking the data after entry into databases. The recorded data should have been checked for correctness and completeness before leaving the site. Check site data in the office as early as possible while memories are fresh. If you can use hand-held or robust portable computers to enter data into database files in the field, then the second component does not exist.

Well-designed databases automatically check for values that are out of range or extreme. Manual checking is still needed where non-specific codes (e.g. locations) or a range of values can be recorded (e.g. soil colour – hue, value, chroma). Random checks may be more practical where there are many data.

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Measuring soil

NJ McKenzie, PJ Ryan

Introduction

An overview of how to measure soil during a survey is provided in this chapter. As with sampling, it is assumed the client's needs and the survey's purpose have already been defined. Decisions about measurement determine the survey's usefulness and directly affect field operations and data analysis.

Most land evaluation in Australia has been based on qualitative descriptions of soil and land resources rather than quantitative measurement. Although there have been undoubted efficiencies, the increasing demand for information on the functional attributes of soil (e.g. permeability, available water capacity, nutrient availability) is changing survey practice.

Preliminaries

Data types

Soil and land attributes are measured or described according to some scale.

Nominal attributes – these are ones that can exist in two or more states. An observation at a site is assigned to a class (x), and for two sites A and B one can only say that $x_A = x_B$ or $x_A \neq x_B$ (e.g. colour of mottles, substrate lithology, plant growth form). A nominal attribute may be binary, which simply records presence or absence (e.g. of a species), or multistate, where more than two states are possible (e.g. type of segregation). Multistate variables may be further divided into exclusive multistates (only one state per site) or non-exclusive multistates (one or more per site).

Ordinal attributes – these have discrete classes that are ordered, though the differences between classes cannot be placed on a constant scale. Ordinal attributes are ranked, where the difference between class 1 and class 4 is greater than between class 1 and class 2, but the intervals between classes are not necessarily equal; only $x_A > x_B$ and $x_A < x_B$ can be distinguished (e.g. soil mottle abundance classes and frequency of inundation as per McDonald et al. 1990).

Interval attributes – these are measured on continuous scales but there is no true zero, although A may be said to be $x_A - x_B$ units different from B (e.g. pH, temperature in °C).

Ratio scale attributes – these are also measured on continuous scales but have a true zero and hence if $x_A > x_B$ then it is possible to say that A is x_A/x_B times larger than B (e.g. soil thickness and temperature in kelvins).

There are more complex types of data that arise in land resource survey. *Serially dependent attributes* occur where a record for a particular attribute depends on the presence of another (e.g. the abundance, size or colour of mottles can be determined only if mottles are present).

Profile attributes occur where several measurements of the sample variable are linked and it is the set of measurements that is of interest (e.g. variation in clay percentage down a soil profile). In this case, the pattern of variation is usually of interest (e.g. for defining texture-contrast profiles).

Interval and ratio attributes are the easiest to analyse statistically. Many of the attributes recorded in surveys, especially soil morphology, do not fit a convenient numerical form and this hinders the adoption of quantitative methods.

Material units

The analysis of soil is sometimes complicated through the use of incompatible or inappropriate units of measurement. Three common problems arise.

Gravimetric versus volumetric units

Conventionally, soil chemical data have been reported in gravimetric terms (i.e. as a quantity per unit mass of soil). However, conversion to a volumetric basis is required for some practical applications and a measurement of the bulk density is needed (see McKenzie and Cresswell 2002).

Fine earth versus whole soil

Another convention is for soil chemical and physical data to refer to the fine-earth component. The fine-earth component is the material that can pass through a sieve with a 2-mm mesh after the soil has been dried and gently crushed. Some care is needed, therefore, when interpreting data in soils with a large proportion of coarse fragments because these effectively diminish the amount of substance in a given volume of soil in the field. For example, a soil with an organic carbon content of 2.0% in the fine earth but a coarse fragment content of 50% will, effectively, have a 1.0% content on a whole-of-soil basis.

Estimate the content of coarse fragments and pay particular attention to circumstances where the coarse fragments are porous or reactive (Cresswell and Hamilton 2002), or where stones or boulders are not included in the specimen used for laboratory analysis because they would constitute a large proportion of the soil volume.

Euclidean versus material coordinates

Soils that change volume with time can create difficulties for sampling and comparison of soil profiles if standard depths of sampling are used. Volume change in soil can be caused by tillage, compaction resulting from machinery and stock, particular clay minerals (e.g. smectites), oxidation (e.g. of soil organic matter in drained peats), and dewatering of saturated materials. Change of volume influences measurements and analyses of water, carbon and solutes. Smiles (1997) and Ringrose-Voase et al. (2000) provide good introductions to methods for dealing with volume change.

Conventional field measurement

Site description

As a minimum, describe sites using the methods outlined in McDonald et al. (1990). Several aspects of this reference have been improved and await inclusion in a new edition of the Field Handbook. In the meantime, consider the following.

Land use – the scheme in McDonald et al. (1990) has been superseded by the new national approach for classifying land use and management (see *Chapter 9*).

Litter and coarse woody debris – protocols for sampling and estimation of total carbon density have been developed for the National Carbon Accounting System (McKenzie et al.

2000). These include procedures for sampling the site and estimating carbon in coarse woody debris, surface litter and roots.

Substrate – regolith survey methods for mineral exploration have been refined since the publication of McDonald et al. (1990). Classifications of substrate materials have been improved and the scheme in Pain et al. (2000) should be considered in addition to Speight and Isbell (1990) (see *Chapter 4*).

Describing soil morphology

Observations of soil morphology are best made in a freshly dug pit or a soil core of large diameter. Many soil morphological data have been recorded by unsuitable methods including thin-walled samplers and hand augers (see *Chapter 16* for appraisal of various approaches).

Specimen collection

It is common practice to collect specimens that span the whole profile (i.e. sampling is continuous down the profile). This method differs from taking specimens at the centres of selected sampling intervals. Our recommendation is that, within the general guidelines below, base the subdivision of the profile on horizons and not on fixed depth intervals. Sampling of these layers is continuous when disturbed specimens are collected.

Use a maximum sampling interval of about 0.1 m in the upper 0.3 m of the profile and use a maximum interval of 0.3 m between 0.3 m and 2.0 m (i.e. some thick horizons may be sampled at two or more depths). Some studies require smaller intervals (e.g. for acidification and nutrient work, the first few layers may need to be 50 mm thick at most). Below 2 m, the sampling interval should be sufficient to characterise whatever is found. These guidelines are intentionally approximate to allow flexibility in sampling profiles that have clear horizon boundaries. For soils with gradual or diffuse boundaries, or with very thick horizons, sampling at standard intervals is recommended (e.g. 0.1 m, 0.2 m, 0.3 m, 0.6 m).

Where only two or three layers can be selected for physical characterisation, emphasise layers that exert most control on the physical environment. These will normally include: the A1 horizons, the top of the B horizon (particularly if it hinders movement of water and air), and the base of the profile. Unless there is a reason for characterising the upper or lower boundary of the layer (e.g. when a crust or pan is present), take cores and clods from the centres of the selected intervals.

Physical measurement often requires the collection of undisturbed specimens, whereas chemical determinations are usually made on disturbed specimens. The preferred types of specimen for some attributes are summarised in Table 17.1. Some measurements require the natural structure of the soil to be maintained. In others, loose material that has been broken or ground will be suitable. The degree of development of soil structure, soil water content, and the possible effects of distortion will influence the size of specimen and the care necessary in handling (see *Chapter 16* for more detail).

Time of sampling

Some soil properties vary with time because of changes in water content. Sample the soil when the property of interest is most important or least variable. For example, physical properties of a cultivated soil are least variable immediately after harvest because consolidation of the tilled layer is effectively complete. McKenzie and Cresswell (2002) provide further guidance on time of sampling in relation to water content, water repellence, root activity and management practices.

Table 17.1 Preferred specimen types for soil physical determinations (McKenzie and Cresswell 2002)

Measurement	Preferred specimen type	Alternative	No. of replicates ^A	Comments
Bulk density and pore space relations	Undisturbed small core	Large clod	3–5	Field measurement methods available
Matric potential: 0–10 m	Undisturbed small core	Large clod	2–4	
Matric potential: –10 m to –150 m	Small aggregates (1–5 mm)	Ground and sieved soil (<2 mm)	1–2 ^B	Duplicates are run on separate plates
Water repellence	Ground, sieved oven-dried soil (<1 mm)	–	–	
Saturated hydraulic conductivity: field	<i>In situ</i> measurement with twin rings	Rainfall simulator	3–7 ^C	Larger soil volumes are characterised by the rainfall simulator (1–15 m ²)
Unsaturated hydraulic conductivity: field	Tension infiltrometer	–	3–5	
Saturated hydraulic conductivity: laboratory	Undisturbed large core	Undisturbed small core	3–5	
Unsaturated hydraulic conductivity: laboratory	Undisturbed large core ($0 < \psi - 100$ mm) or small core ($\psi > \sim -50$ mm) ^D	Small core	3–5	
Emerson dispersion test	Small aggregates (5–8 mm)	–	2 aggregates per beaker	Extra determinations for each type of mottle when present
Clay dispersion	Ground, sieved air-dried soil (<2 mm)	–	–	
Soil erodibility: water	Ground and sieved soil (<2 mm)	–	–	Non-dispersed particle size analysis
Soil erodibility: wind	2–3 kg air-dried soil with minimal disturbance	–	–	
Coefficient of linear extensibility (COLE _{std})	Large clod (50–200 cm ³)	–	3–5	LS_{mod} uses ground and sieved soil (<2 mm)
Linear shrinkage (LS)	Ground and sieved soil (<0.425 mm)	–	1–2 ^B	
Liquid and plastic limits	Ground and sieved soil (<0.425 mm)	–	1–2 ^B	
Soil strength: micro-penetrometer	Undisturbed small core ($\psi = -1.0$ m)	–	10	Depends on core size (maximum of ~ 5 determinations per small core)
Modulus of rupture	Ground and sieved soil (<2 mm)	–	–	

Measurement	Preferred specimen type	Alternative	No. of replicates ^A	Comments
Particle size distribution	Ground and sieved soil (<2 mm)	–	1	Coarse fraction (>2 mm) removed and measured during preparation

^A The number of replicates is indicative. The required accuracy and precision for an investigation may demand more replication.

^B A single determination is normally adequate in a well-run laboratory. Duplicates or standard specimens are included for quality control.

^C The number of duplicates refers to the larger ring size – more determinations with the smaller rings are required.

^D Soil water potential.

Laboratory analysis

The following sections are based largely on Beattie (1988), and methods for chemical and physical analysis are described in accompanying Handbooks (Rayment and Higginson 1992; McKenzie et al. 2002; Rayment et al. in press). Laboratory data are used to complement field information. Analysis cost, usually several hundred dollars per site, means that laboratory data should be gathered only when field observations (and less expensive field tests) are inadequate. Have a clear plan for the use of laboratory data, and make sure they increase the precision and cost-effectiveness of the survey.

Soil is measured in the laboratory for pedological, edaphological and engineering purposes. Tables 17.2 to 17.5 list the most common attributes and their use. Whereas these tables identify preferred methods, review the selection for a given study. McKenzie et al. (2002) and Rayment et al. (2007) provide general recommendations on preferred methods. They also describe quality control, standards and interlaboratory correlation.

Record both the methods used for laboratory analysis and the results. Different methods return different results for many soil attributes especially nutrient availability and some physical attributes (e.g. hydraulic conductivity). Standard method codes are regularly updated, so check with the relevant database administrator for the latest information. See Table 17.6 for a guide to the precision of reporting for analytical data.

Tables 17.2 to 17.5 emphasise chemical, physical and mineralogical attributes – biological properties have not been considered. Most biological measurements (e.g. species diversity, abundance, biomass) demand much in terms of time and resources – routine characterisation has not been undertaken in standard land resource survey. Soil biologists are starting to identify what properties are important in resource assessment and monitoring, and techniques to measure them are being developed. There is a great deal to learn about the diversity and function of soil organisms in Australian landscapes, and capturing this knowledge could be valuable.

New systems for soil measurement

A revolution in environmental sensing and measurement is underway. Measuring the soil is now receiving greater attention because of the demands of precision agriculture and the need for better techniques for surveys of contamination and for remediation. Improvements in land resource survey are now constrained by the cost of conventional measurement and an over-reliance on soil morphology (see *Chapter 1*). This section is drawn from McKenzie et al. (2003). It outlines systems for rapid measurement for land resource survey. Some of the techniques are in their infancy; others are well developed in terms of their instrumentation but have few agreed procedures for data analysis and interpretation.

Table 17.2 Laboratory analyses for soil classification and pedogenetic studies

Property	Application
Micromorphology	
Fabric	
Voids	
Pedological features	
Micropeds	Degree of differentiation or segregation of pedological features (correlation with mineralogical, physical and chemical properties); identification of pedological continuity; interpretations for soil classification and genesis
Mineralogy and total analysis of <2 mm fraction	
Sand fraction mineral composition and ratios	Weathering studies; lithological continuity/discontinuity
Clay fraction composition	Weathering studies; correlation with physical and chemical properties and plasmic fabric in studies of soil behaviour
Total silicate composition (major and minor elements)	Correlation of soil materials and parent rock; estimation of change from prior state due to soil formation; identification of lithologic continuity/discontinuity
Physical	
Air-dry water content (105°C)	Conversion of data to standard oven-dry basis; first estimate of colloidal activity
Loss on ignition	Estimate of organic matter and structural water of mineral colloids
Coarse fragments (>2 mm) (see McDonald et al. 1990)	Determination of lithology; lithologic continuity/discontinuity; similarity with parent rock
Particle-size distribution (<2 mm fraction)	Origin of soil materials; correlation with other physical and chemical properties
Fractionation of <2 µm fraction (2–0.2 µm, 0.2–0.08 µm, <0.08 µm)	Activity of clay fraction; correlation with other physical and chemical properties
Bulk density	Estimation of porosity, compaction; correlation with fabric; calculations of soil formation; estimates of constituents on volume basis; correlation with other physical and chemical properties
1.5 MPa water content	Detection of subplastic materials (ratio with per cent clay)
Chemical	
Soil reaction (pH)	Base saturation; soil acidity; sodicity (H ₂ O, 1:5); buffering capacity (0.01 M CaCl ₂); detection of sulfuric horizon (H ₂ O, 1:1); correlation with other physical and chemical properties; NaF (active Al, indicator of allophane)
Total soluble salt, electrical conductivity (TSS, EC)	Identification of salic horizon (% salt more soluble than gypsum in H ₂ O); intensity of leaching; water relationships; ionic strength of soil solution
Chloride	As above
Calcium carbonate	Identification of calcic horizons; intensity of leaching
Gypsum	Identification of gypsic horizons; intensity of leaching
Organic carbon	Classification of organic and peat soils; identification of diagnostic horizons; correlation with other physical and chemical properties

Property	Application
Cation exchange capacity (CEC) Effective cation exchange capacity (ECEC) Exchangeable cations Total exchangeable bases	identification of diagnostic horizons; CEC/clay ratios; interpretations for soil genesis; correlation with other physical and chemical properties
KCl-extractable acidity (Al, H)	Measure of aluminium saturation and for obtaining ECEC
Sodium adsorption ratio (SAR)	
Exchangeable sodium percentage (ESP)	Identification of natric horizon; identification of sodic soils; correlation with other physical and chemical properties
Extractable C, Al and Fe (0.1 M sodium pyrophosphate pH 10; sodium dithionite–sodium citrate)	Identification of spodic horizons not identifiable on field criteria

Not all of these analyses are required for classification nor for any particular pedogenetic study. They would all be required only for complete characterisation of a soil (after Beattie 1988).

Table 17.3 Analytical data for soil management in dryland and irrigated agriculture (after Beattie 1988)

Property	Application
Mineralogical	
Weatherable minerals	Assessment of long-term nutrient resource
Composition of clay fraction (<2 µm)*	Nutrient retention and supply; fixation of plant nutrients; interpretation of many soil properties and qualities (e.g. hydraulic conductivity, infiltration, water retention, drainage, shrink–swell, strength, dispersion, plasticity and stickiness); cation exchange capacity
Physical	
Air-dry water content (105°C)	Conversion of data to standard oven-dry basis
Coarse fragments (>2 mm)	Soil workability; root development; droughtiness
Particle-size distribution (<2 mm)*	Nutrient retention; exchange properties; erodibility; droughtiness; workability; permeability; sealing; drainage; interpretation of most other physical and chemical properties and soil qualities
Bulk density ^A	Effective soil thickness for plant root development; evaluation of soil compaction; aeration; effect of tillage; calculation of nutrient per unit volume; conversion from gravimetric to volumetric water content; correlation with other physical, chemical and biological properties
Soil shrinkage ^A	Assessment of shrink–swell behaviour; soil stability; compactibility; linear extensibility, LE/(% clay) (ratio) to indicate clay groups; pore space relationships; infiltration; correlation with other properties
Aggregate stability and clay dispersion ^A	Susceptibility to surface sealing under rainfall or irrigation; effect of raindrop impact and slaking; permeability; infiltration; aeration; seedling emergence; correlation with other properties

(Continued)

Table 17.3 (Continued)

Property	Application
Size distribution of aggregates (wet or dry sieving)	Soil erodibility; macroporosity; surface water storage and permeability
Available water capacity (water contents at 10 kPa–1.5 MPa)	Estimate of plant available water capacity; correlation with other physical, chemical and biological properties
Soil water characteristic ^A	Pore space relations (e.g. aeration, porosity); water storage; soil structure and stability; water holding capacity and available water capacity; soil stability; workability; correlation with other properties
Hydraulic conductivity ^A	Calculation of water balance; drainage
Chemical	
Soil reaction (pH) (1:5, soil: water suspension; 0.01 M CaCl ₂) ^A	Nutrient availability; nutrient fixation; toxicities (especially Al, Mn); liming; sodicity; correlation with other physical, chemical and biological properties
Organic carbon	Nutrient availability, retention and fixation (especially N, P, S); cation exchange capacity; soil stability and workability
Active iron, aluminium and manganese	Phosphorus fixation; cobalt occlusion; aluminium and/or manganese toxicity
Exchangeable bases (Ca, Mg, K)	Nutrient supply (correlate with plant response); Ca/Mg, Ca/K and Mg/K ratios
Total nitrogen	Potential N supply
Total phosphorus	Potential P supply
Total K	Potential K supply
Extractable sulfur	Estimation of sulfur supply
Extractable micronutrients	Availability when correlated with plant response; identification of toxicities, antagonisms
Electrical conductivity (EC _e or EC _s) ^A	Appraisal of salinity hazard in soil substrates or groundwater, total soluble salts
Chloride ^A	Toxicity; salt and water movements
Soluble cations and anions (saturation extract) ^A	Assessment of saline and sodic soils; determination of sodium, potassium and monovalent adsorption ratios (e.g. SAR, KAR, MAR); prescription of amelioration treatments
Cation exchange capacity and exchangeable cations	Nutrient status; calculation of percentage exchangeable sodium (ESP), potassium (EKP), monovalent cations (EMP), assessment of other physical and chemical properties, especially clay dispersion, shrink–swell, water movement, aeration
Carbonates ^A	Phosphorus retention and fixation in alkaline pH range; physical effects on soil texture and consistence
Gypsum ^A	Appraisal of soil salinity and/or sodicity; soil amelioration (high clay or sodic soils or potassic soils); beneficial soil mixing

^AAlthough all properties listed are relevant, those marked with an asterisk are especially important for management of irrigated soils.

Table 17.4 Laboratory data for the assessment of soil qualities (after FAO 1983)

Soil quality	Subdivision	Laboratory data
Nutrient availability	Nutrient levels in topsoil	Total nitrogen, available phosphorus
		Exchangeable K
		Other nutrients as implicated
	Availability/fixation indicators (lower horizons)	Soil reaction (pH)
		Ratio of Fe ₂ O ₃ to clay
		Allophane (presence, absence, pH in NaF) ^A
	Nutrient renewal capacity (lower horizons)	Weatherable minerals, total phosphorus, K and sulfur
	Modifying factors	Active aluminium
		Acidity (pH, H ₂ O)
		Phosphorus retention
		Reserve K
Nutrient retention	Exchange sites (lower horizons)	Cation exchange capacity
		Total exchangeable bases
		Organic matter
		Sign of net surface charge of acidic soils with variable charge colloids
	Leaching intensity (lower horizons)	Base saturation
		Soil permeability
Rooting conditions		Bulk density
Excess of salt	Salinity (topsoil and lower root zone)	EC _e dS/m
		Total soluble salts.
	Sodic or potassic soils	ESP, EKP, EMP
		SAR, KAR, MAR
Soil toxicities	Aluminium	Al saturation pH (H ₂ O, 1:1) < 5.0 (mineral soils)
	Manganese	Soluble Mn, ppm
	Acid sulfate	pH (H ₂ O, 1:1) < 3.5 (mineral soils)
	Calcium carbonate and gypsum	Percentage in root zone
Soil degradation hazard	Physical	Dispersion index
	Chemical (acidification)	Index of crusting: pH monitoring
	Biological	Organic matter monitoring

^ARare in Australia.

Table 17.5 Laboratory data for engineering uses of soils and for soil conservation (after Beattie 1988)

Property	Application
Physical	
Soil water content	Calculations, corrosivity
Particle-size distribution (% passing sieves: No. 4 (4.76 mm), No. 10 (2.0 mm), No. 40 (0.42 mm), No. 200 (0.074 mm); coarse fraction 75 mm)	Unified and AASHO classifications; shallow excavations; soil limitations for dwellings; septic tank absorption fields; sewage lagoons; land fill; local roads; road fill; source of sand, gravel, topsoil; drainage; graded banks, diversion and absorption banks
Bulk density	Conversion from gravimetric to volumetric; shrinkage potential
Shrinkage potential (linear shrinkage, coefficient of linear extensibility)	COLE classes; stability of structures; shallow excavations; soil limitations for dwellings, roads, parking areas, road fill
Permeability (saturated hydraulic conductivity)	Permeability classes; septic tank absorption fields; sewage lagoons; land fill; road fill; irrigation; conservation structures
Available water capacity	AWC classes; irrigation
Shear strength	Compacted embankments; farm dams; conservation structures
Compressibility, compaction characteristic	
Permeability of compacted soil	
Emerson aggregate test	Susceptibility to slaking, dispersion, and piping
Liquid and plastic limits (Atterberg limits)	Plasticity index; soil stability; Unified Soil Classification System
Chemical	
Soil reaction	pH range classes; corrosivity of concrete
Salinity and alkalinity	Salinity classes; corrosivity; source of topsoil; irrigation
Organic matter	Sewage lagoons; compactability
Corrosivity (EC at moisture equiv., EC_e ; total or extractable acidity; soil texture)	Corrosivity classes for uncoated steel
Sulfates, acidity (soil texture)	Corrosivity towards concrete
Exchangeable sodium percentage (ESP), Exchangeable K percentage (EKP), Exchangeable monovalent cations (EMP)	Susceptibility to dispersion and piping; stability

For mineralogy classes interpreted for likely engineering performance, see Mausbach (1982).

Table 17.6 Precision of reporting analytical data

Whole digit	Round to: One decimal	Two decimals
Particle size classes (%)	Loss on ignition (%)	Air dry water content (air-dry, %)
Water content (%) (10–1500 kPa)	Organic carbon (%)	Bulk density (Mg/m ³)
Liquid and plastic limits (%)	Soil reaction (pH)	Coefficient of linear extensibility
Aggregate stability classes	Pyrophosphate-extr. C, Al, and Fe (%)	Total K (%)
Electrical conductivity (dS/m)	Exchangeable cations (cmol(+)/kg)	Total sulfur (%)
Cation exchange capacity (cmol(+)/kg)	Extractable acidity Al, H (cmol(+)/kg)	Total nitrogen (%)
Effective cation exchange capacity (Σ exch. cations)	Total soluble salts (%)	Total phosphorus (%)
Exchangeable sodium ratio	Chloride (%)	
Extractable micronutrients (ppm)	Sulfate (%)	Carbonate (%)

Several of the most promising techniques for rapid measurement in the field are based on spectral reflectance imagery or imaging spectroscopy of soil specimens. These use measurements of reflected or emitted radiation at diagnostic wavelengths within the electromagnetic spectrum. Passive systems (e.g. those commonly used in satellite-based remote sensing) rely on the sun's reflected radiation (see *Chapter 11*). Active systems are more useful for soil sensing and they rely on materials being illuminated at close range by sources with known spectral characteristics and brightness – analysis of the absorbed, transmitted or reflected radiation is used to identify constituents. Although spectroscopic methods have a long history in science and technology, only in recent decades have miniature systems become available at acceptable cost.

Mid infrared

Many soil properties are related to soil constituents that can be recognised by the number, position and sharpness of characteristic peaks in their infrared spectra. Infrared methods have advantages over X-ray methods in that spectra are sensitive to amorphous organic and inorganic compounds, adsorbed water and crystalline minerals (e.g. clay minerals) (Janik et al. 1995).

A significant advantage of mid infrared is its sensitivity to quartz, a mineral that makes up most of the silt and sand fraction in Australian soils. An ability to estimate the abundance of quartz in a specimen therefore allows good prediction of clay content (i.e. the complement of percentage sand plus silt content). In combination with determinations of organic constituents and clay mineralogy, this allows good characterisation of many physical and chemical properties. The technique has been successfully used to measure various soil properties including organic carbon (OC), total nitrogen (N), carbonate (CO_3^{2-}), cation exchange capacity (CEC), exchangeable cations (calcium, Ca; magnesium, Mg; potassium, K; sodium, Na), phosphorus buffer capacity, pH, lime requirement, water content at a range of potentials and particle size.

Infrared spectra contain an enormous amount of information on soil constituents and, until recently, their complexity was overwhelming. The advent of robust multivariate statistical methods (e.g. partial least squares), now ensure more effective exploitation. These statistical

methods require analysis of soil materials with known chemical and physical properties (i.e. determined by conventional chemical and physical methods). The spectra of these form a calibration data set. The calibration set is then used to estimate soil properties for spectra determined on soils that have not been characterised by chemical or physical methods.

Specimens of soil for analysis are usually in the form of finely ground powders that have been air-dried. There is short preparation time, and scanning usually takes less than 2 minutes. Commercial instruments suited to field use are available, but experience to date in Australia indicates that they are still not sufficiently robust for this. It is cheap to characterise and analyse soils with mid infrared: a standard set of analyses costing several hundred dollars with conventional methods in the laboratory can be obtained for around A\$20.

Mid-infrared measurement for rapid soil characterisation will be feasible in routine land resource survey when there are comprehensive calibration sets for the range of soil materials encountered across Australia. There is also a need for mechanical collection and preparation of specimens, as well as a system for direct scanning of soil cores.

Near infrared

The principles of measurement in the near-infrared range are similar to those for the mid infrared. Commercial units are available, and they are used routinely in a wide range of laboratory, industrial and field settings. Applications of near infrared spectroscopy directed towards rapid field measurement have demonstrated the technology's capacity to estimate clay, organic matter (OM) and soil water contents (Sudduth and Hummel 1993a,b; Viscarra Rossel and McBratney 1998a).

Handheld near-infrared spectrometers with inbuilt data analysis capabilities and standard spectra have been developed for field geology. These devices (e.g. PIMA II; Integrated Spectronics 2006) allow measurement of the spectra of rocks and minerals in the field, thereby assisting with mineral identification, determining the degree of crystallinity, detecting variations associated with weathering and assessing the extent of isomorphous substitution of elements in some crystal structures.

The mid-infrared range of the electromagnetic spectrum is better suited than the near-infrared range for predicting most soil properties. However, near infrared and mid infrared can be used in a complementary way together with visible and ultraviolet measurements (Viscarra Rossel et al. 2006).

Visible and near-visible reflectance

Various sensors in the visible and near-visible range have been used for close-range direct soil measurement, but most have been restricted to a few frequencies (e.g. Shonk et al. 1991; Shibusawa et al. 2000, 2003). These methods invariably require recalibration according to the soil type and landscape. Several soil probes have been developed for measuring soil colour, including imaging penetrometers (e.g. Rooney et al. 2001; Integrated Spectronics 2006). Local calibrations of soil colour have been used for predicting soil properties including organic carbon (Viscarra Rossel et al. 2003).

Hyperspectral sensing in the visible and near-visible range can be applied to soil specimens (e.g. sieved and dried fine-earth fraction or intact cores) or to the land surface. Again, its use in routine land resource survey requires the development of systems for mechanised collection and preparation of specimens and scanning cores.

Ion-selective field effect transistors

Ion-selective field effect transistors (ISFETs) are integrated circuits with ion-selective membranes applied to the gate of the sensor. They can be used to measure concentrations of ions in

a solution. The ISFETs have small dimensions, rapid response times (milliseconds), low output impedance, high signal-to-noise ratio, require only small volumes and can be mass produced (Birrell and Hummel 2001). When coupled with an automatic system for specimen preparation and a flow-injection analysis system, they can become effective real-time sensors (see Adamchuk et al. 2003).

One can use ISFETs for determinations of substances in a soil solution. These include nitrate (Birrell and Hummel 2001), pH, lime requirement (Viscarra Rossel and McBratney 1998b), Ca, K, Na and ammonium (see Birrell and Hummel 2001 references).

Implementation of the technology for real-time measurement is hindered by the need for rapid specimen collection and difficulties in extracting the soil solution. Factors affecting performance include soil conditions, engineering design and the kinetics of chemical reactions in the sampled solution. Viscarra Rossel and McBratney (2003) consider the latter in relation to measurement of lime requirement. The major challenge for implementation of ISFET technology is construction of robust equipment for rapid collection of specimens and extraction of solutions.

Electrical conductivity

Unlike the previous methods that rely on either spectroscopic principles or direct sensing of soil extracts, several geophysical methods can be used to measure the ease with which an electrical current passes through soil and deeper regolith. The methods rely on either electromagnetic induction or resistivity and they can be used to characterise large volumes of soil (depths from <1 m to several hundred metres) although the extent of measurement is often not specified with great precision.

Electromagnetic induction

This method uses a varying magnetic field to induce alternating currents in the ground in a way that ensures their amplitude is linearly related to the EC of the soil. The magnitude of these currents is registered by measuring the magnetic field they, in turn, generate. Unlike resistivity measurement, this technique does not require an instrument in contact with the soil. As a result, measurement and survey can be rapid. McNeill (1980) provides a good account.

Electromagnetic induction survey (or EM survey) has become popular in Australia, particularly to support precision agriculture. Commercial instruments are available and, when coupled with Differential Global Positioning Systems (DGPS), they allow rapid mapping. When used appropriately (i.e. with thorough checking in the field), the method is invaluable for mapping some soil properties in particular landscapes. However, total reliance on EM survey as a surrogate for soil survey is unwise, as even a rudimentary understanding of the technique and insight into natural soil variation will show.

Because most soil and rock minerals are good electrical insulators (except e.g. for iron minerals magnetite, maghemite, pyrite), the conductivity as sensed by an EM unit depends on electrolytes, and therefore on the pore-water system. Consequently, the following factors are important:

- shape, size and connectivity of the pore system
- water content (i.e. degree to which the pore system is filled and interconnected)
- concentration of dissolved electrolytes in the soil water
- temperature and phase of the pore water (frozen soil is rarely a consideration in Australia)
- amount and composition of colloids.

While clay content, EC of the soil solution, and water content are often recognised as the controlling factors that need to be accounted for when calibrating EM measurements (e.g. Williams

and Baker 1982; Williams and Hoey 1987), it is not that simple. It is the pore system and its contents rather than the clay content *per se* that should be considered. Soils containing significant amounts of clay usually have a pore geometry dominated by finer pores, so, in comparison with a sandy soil, greater proportions of these pores are filled and connected (at comparable water contents) – giving rise to the larger EC. Soil bulk density should also be considered because it determines total porosity. Clay soils in most cropping areas usually have a substantial CEC, and cations in solution are in equilibrium with the charged clay surface – such cations also contribute to the electrolyte concentration. Finally, colloids – particularly those associated with organic matter – may also contribute to the measured conductivity.

Most ground-based electromagnetic measurement in Australia is undertaken using one of the commercial units produced by Geonics Ltd. These units can be configured to measure conductivity in the immediate soil profile (to about 1.5 m for the EM38) or deeper layers (~6 m for the EM31, and down to 60 m with the EM34). Using classical EM instruments, the depth of measurement is affected by coil spacing and frequency. The EM38 and other similar instruments have both of these fixed. Refer to O’Leary (2006) for protocols and operating procedures for electromagnetic measurement.

Resistivity

One can measure the resistivity of soil (i.e. the inverse of conductivity) by imposing a voltage between electrodes placed in the soil. The technique has been used for a long time in geophysics, and various electrode configurations can be used to control the volume and depth of measurement. Resistivity measurements using conventional equipment are slower than measurements by electromagnetic induction, and physical interpretation of results can be complex. The soil factors noted in the previous section affect resistivity measurements in the same way.

Several commercial systems are available including the VERIS EC Mapping System from the United States and the French ARP system. Both use rotating metal discs as electrodes. The discs either cut several centimetres into the soil (VERIS) or have small probes that penetrate into the soil (ARP). Continuous recording of resistivity and conductivity is possible if the cart carrying the devices is towed across the landscape. Dabas and Tabbagh (2003) provide a good comparison between resistivity (VERIS3100, ARP) and electromagnetic systems (EM38). Not surprisingly, they conclude that resistivity methods are preferable because of better calibration and depth control.

Ground penetrating radar

Ground Penetrating Radar (GPR) is a subsurface imaging technique that uses the reflection of very short pulses of electromagnetic energy from dielectric discontinuities in the ground to form an image of the subsurface. Almost any reasonably abrupt variation in material type will produce a reflection of energy and show up as an image. Since water has a high dielectric constant (~80) compared to most dry soil materials (~5), soil water content is important. However, slowly changing water contents are hard to detect with GPR and, in general, water profiling is not possible with traditional types of GPR. More rapid changes, such as wetting fronts, are easier to detect, and this use of GPR can be used in irrigated regions.

The performance of GPR depends on the material. Under good conditions, near optical clarity is obtainable; in poor conditions (e.g. high clay and water contents), however, GPR is almost useless. The high cost and complexity of GPR, coupled with the need for expertise in operation (and image processing and interpretation), means that subsurface imaging is likely to be limited to particular investigations of subsurface features where the unique imaging capability can be of value. Although the method is of interest to land resource survey, GPR in its current form is unlikely to become a routine method.

Gamma radiometric spectrometry

Gamma spectrometry for measuring soil properties can be done with airborne or vehicle-mounted systems (see *Chapter 13*). Gamma radiometric spectrometers can be mounted on field vehicles, and commercial companies now provide services, in combination with electromagnetic induction, to make maps at paddock scales. This combination of sensors is particularly effective: the gamma radiometric data relate strongly to the solid mineral component of soil, whereas the electromagnetic induction data relate more to the electrolyte properties of the soil solution. Direct field measurement of soil properties is always required for calibration.

Gamma radiometric survey has a well-developed technology for both air-borne and ground-based measurement. Down-borehole units are used for mineral exploration and contamination investigations (e.g. Adams and Robitaille 2000). Although there have been some recent and notable improvements in spectral analysis, most benefit for agriculture and forestry should come from encouraging operators to carefully interpret gamma radiometric survey results and promote the use of multiple sensing systems (e.g. EM survey). As with EM survey, an appreciation of the physical principles of measurement and field pedology is essential to avoid spurious correlations and interpretations.

Deeper measurement using core scanning or down-borehole technology

Most of the measurement technologies considered so far are better suited to near-surface or surface measurement (i.e. upper 0.3 m) than to the deeper soil. However, deeper observations are needed to determine subsoil constraints to root growth, characterise the soil water regime, and to assess potential off-site impacts. Some of the techniques provide insights about deeper layers (e.g. EM survey and to a lesser extent gamma radiometric spectroscopy), but there is still a need to develop systems of rapid measurement to characterise the complete soil profile, at least to 1 m to 3 m.

Undisturbed soil cores spanning deeper layers can be collected readily with small drill rigs with either push-tubes or Proline samplers. There is an opportunity to apply many of the methods considered above to an automated scanning system for soil cores. Commercial units have been developed for sediment and rock cores (e.g. Geotek 2001) that include gamma density (attenuation of gamma rays provides a means for measuring water content and bulk density), natural gamma radiation, electrical resistivity, magnetic susceptibility, digital photography and seismic properties. These units can be modified to include mid-infrared or near-infrared sensors. Rapid measurements on cores would allow soil surveys to be undertaken more efficiently and it would be a natural complement to vehicle-mounted sensor systems.

Minimum data sets for land resource survey in Australia

Site and profile data can range from the allocation of a profile to a taxonomic system through to results from detailed field and laboratory measurements. Although the latter are useful, they are also costly. The features of soil description at four levels of detail (A–D) are presented in Table 17.7. They are a modification of the hierarchies recognised by Hackett (1983, 1988) and Bouma (1989).

Most agencies in Australia collect large quantities of data at Level A and B, with only a few devoting significant resources to Level C. Level D data are rare, although they are often needed as inputs to simulation models. Realistic representations of soil and land processes in computer-based models can also be achieved with Level C data (Hackett 1988). If land resource survey is to move beyond the provision of static descriptions of land resources, then more efficient

Table 17.7 Levels for describing soil in land resource assessment – all measurements are georeferenced

Level	No. of variables	Time required	Type of data	Nature of description	Interpretations
A	1	1–30 min	Soil name (e.g. soil profile class)	Broad, qualitative, static, and empirical	General statements of suitability for major types of land use
B	50–200	20–60 min	Profile description (e.g. morphology according to McDonald et al. 1990)	Can be detailed, but qualitative, static, and semi-empirical	Specific statements on some limitations to land use. Predictor variables for some pedotransfer functions
C	80–400	2–20 days	Profile description and laboratory data	Detailed, quantitative, and static, but mechanistic	Specific statements on most forms of limitation to land use. Predictor variables for most pedotransfer functions
D	100–500	10–30 days	Direct measures of parameters controlling soil processes	Detailed, quantitative, dynamic, and mechanistic	Dynamic and probabilistic prediction of processes controlling land use. Inputs to simulation models

Table is based on Hackett (1988), Bouma (1989), and McKenzie (1991). Specific variables at Levels B, C and D are listed in Tables 17.8, 17.9 and 17.10.

procedures are needed for the collection of data at Levels C and D. Pedotransfer functions have a role as well (see *Chapter 22*). Comprehensive soil databases are most effective when consistent methods have been used for measurement (e.g. for generating reliable pedotransfer functions). One should specify and adhere to a minimum data set. Minimum data sets are presented in Tables 17.8 to 17.10 for Levels B, C and D.

The minimum data sets should in no way constrain collection of more detailed analytical data. Note that many of the soil properties listed in Tables 17.2 to 17.5 are not included in the minimum data sets because they are specific to particular groups of soils. It may be beneficial later to specify minimum data sets for well-defined groups of soils and related environments.

Table 17.8 Level B minimum data set for land resource survey in Australia

Attributes	Measurement method ^A	Comments ^B
Site and location		
Location (coordinates, datum, projection)	GPS	See <i>Chapter 16</i>
Observation type, and reason for lower depth-limit of sampling		Soil pit or large diameter core, see <i>Chapter 16</i>
Date		
Land use		See <i>Chapter 9</i>
Morphology	McDonald et al. (1990)	
Layer thickness, boundaries (shape and distinctiveness)		
Horizon designation		
Matrix colour, mottle colour, abundance, contrast and size		
Field texture and coarse fragment size and abundance		
Structure grade, size, and type		
Macropores (type, areal porosity)		
Segregations (size, type)		
Pan presence/absence, type		
Substrate type and permeability		
Chemical properties	Rayment and Higginson (1992)	Rayment et al. (in press) will provide improved methods
pH		
Electrical conductivity		
Physical properties		
Bulk density and porosity	503.01 or 503.04	503.05–503.09 when coarse fragments are present
Water repellence	505.01	
Dispersion class	513.01	

^A Follows Rayment and Higginson (1992) and McKenzie et al. (2002).

^B Chapter numbers refer to this publication.

Table 17.9 Level C minimum data set for land resource survey in Australia

Attributes	Measurement method ^A	Comments
Site and location		
Location (coordinates, datum, and projection)	GPS	See Chapter 16
Observation type, and reason for lower depth-limit of sampling		See Chapter 16
Date		
Land use		See Chapter 9
Morphology	McDonald et al. (1990)	Soil pit or large diameter core
Layer depths, boundaries (shape and distinctiveness)		
Horizon designation		
Matrix colour, mottle colour, abundance, contrast and size		
Field texture and coarse fragment size and abundance		
Structure grade, size, and type		
Macropores (type, areal porosity)		
Segregations (size, type)		
Pan presence/absence, type		
Substrate type and permeability		
Chemical properties	Rayment and Higginson (1992)	Rayment et al. (in press) will provide improved methods
pH		
Electrical conductivity		
Organic carbon		
Exchangeable Ca, Mg, K, Na		
Cation exchange capacity		
Carbonate content		
Physical properties		
Bulk density and porosity	503.01 or 503.04	503.05–503.09 when coarse fragments are present
Water repellence	505.01	
Dispersion class	513.01	
Particle size analysis	517	
Soil shrinkage	518.01	When clay + silt >25%

^A Follows Rayment and Higginson (1992) and McKenzie et al. (2002).

Table 17.10 Level D minimum data set for land resource survey in Australia

Attributes	Measurement method ^A	Comments
Site and location		
Location (coordinates, datum, and projection)	GPS	See <i>Chapter 16</i>
Observation type, and reason for lower depth-limit of sampling		Soil pit, see <i>Chapter 16</i>
Date		
Land use		See <i>Chapter 9</i>
Morphology	McDonald et al. (1990)	
Layer depths, boundaries (shape and distinctiveness)		
Horizon designation		
Matrix colour, mottle colour, abundance, contrast and size		
Field texture and coarse fragment size and abundance		
Structure grade, size, and type.		
Macropores (type, areal porosity)		
Segregations (size, type)		
Pan presence/absence, type		
Substrate type and permeability		
Chemical properties	Rayment and Higginson (1992)	Rayment et al. (in press) will provide improved methods
pH		
Electrical conductivity		
Organic carbon		
Exchangeable Ca, Mg, K, Na		
Cation exchange capacity		
Total P and P sorption		
Carbonate content		
Physical properties		
Bulk density and porosity	503.01 or 503.04	503.05–503.09 when coarse fragments are present
Soil water characteristic	504.01 and 504.02	
Water repellence	505.01	
Saturated hydraulic conductivity	510.01 (510.02 or 510.03 if required)	507.01 is a field-based alternative
Unsaturated hydraulic conductivity	510.04	508.01 is a field-based alternative. 510.05 can be used if large cores are not available

(Continued)

Table 17.10 (Continued)

Attributes	Measurement method ^A	Comments
Dispersion class	513.01	
Particle size analysis	517	
Soil shrinkage	518.01	When clay + silt >25%

^A Follows Rayment and Higginson (1992) and McKenzie et al. (2002).

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Qualitative survey

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Introduction

Most land resource survey in Australia has been qualitative. The methods include integrated, free, stratigraphic and grid survey. This chapter describes each method and compares their merits. Integrated, free and stratigraphic surveys have much in common. The strategies for sampling in each approach are described before sections on the research phase, the mapping phase, correlation and validation.

Methods for qualitative survey

Integrated survey

Description

Integrated survey refers to a general class of methods and includes land system surveys (Christian and Stewart 1968), soil–landscape surveys (e.g. Northcote 1984) and ecological surveys (Rowe and Sheard 1981). Integrated surveys place great reliance on presumed correlations with environmental features observable in remotely sensed imagery (e.g. air photos, satellite images) or maps. Geological, geomorphic and vegetation distinctions are emphasised. Field observations are intended primarily not to locate boundaries but to identify the soils and vegetation within the areas delineated on air photographs.

There are various forms of integrated survey. In land system survey (Christian and Stewart 1968; Austin and Basinski 1978), information is provided at two levels of spatial resolution (see Table 3.2). At the most detailed are *land facets*, which are mappable entities but in practice are not usually mapped. Land facets are defined as a group of related sites that for practical purposes can be considered uniform in terms of landform, soil and vegetation. At the next level are *land systems* – these are defined as assemblies of land facets that are either or both geographically or geomorphically related and throughout which there is a recurring pattern of landforms, soils and vegetation (Christian and Stewart 1953; 1968).

The recurring pattern is used to extrapolate point data and only a few occurrences of any single land system will be sampled; the relationship between land characteristics is assumed to apply even when a land system is spatially disaggregated. In contrast, more detailed integrated surveys often treat each land unit tract as a unique entity (i.e. the Unique Mapping Areas of Speight 1988) and point data are extended only as far as the tract boundary (Margules and Scott 1984). Table 18.1 lists the main steps in integrated survey.

Table 18.1 The main steps involved in integrated survey

Step	Description
Collation and research	Gathering of published data and existing information
Mapping	The area is mapped on the basis of distinct air photo patterns; provisional coding of vegetation, landform, and geology is undertaken
Group mapping units	Mapping units are grouped on the basis of biophysical attributes and a sampling plan is designed
Field survey	Data are collected at selected sites and along chosen routes
Revision	Correlations between air photo patterns and landscape attributes are established, confirmed, elaborated, or modified
Land system description and definition	Mapping units are grouped (after any necessary modifications) into a final set of land systems, and a set of component land units is defined for each system.
	Land units are described in terms of geology, landform, soils and vegetation using correlations between attributes to extrapolate from sampled to un-sampled sites.

Integrated surveys have two general premises (Austin and Basinski 1978). First, it is assumed that many land characteristics are interdependent and tend to occur in correlated sets. This implies that attributes observable on air photos, such as vegetation and landform, can be used to predict the distribution of soil attributes that can be only observed at a few points in the field. The second premise is that every land use is constrained by the combined and interacting effects of several land attributes. One implication of this is that the same data and land classification can be used to evaluate areas for a range of uses. General-purpose soil surveys rely on a similar premise.

The utility of integrated survey depends on the degree to which these premises are met. The approach has been used for most low-intensity and medium-intensity surveys. It has been found to be useful in detailed surveys in northern Australia where much of the natural vegetation is intact. In contrast, the cleared lands of southern Australia are more difficult to map using this method.

Strengths

- Rapid appraisals of land resources are possible at less cost than if each resource (i.e. soil, landform, vegetation) were mapped separately.
- By making assumptions about the correlations between soil, landform, parent material and vegetation, surveyors have mapped large areas with little field work.
- The holistic approach may lead to a more realistic assessment of possible land uses because all major environmental constraints are considered (Margules and Scott 1984).

Weaknesses

- An experienced air-photo interpreter can draw a rational and sensible map – nevertheless, the result is his or her individual interpretation of the landscape. Other interpreters will produce different maps because the mapping criteria are not explicit.
- Sampling is subjective.

- The intensities of sampling are rarely adequate to allow a testing of the presumed relationships between readily observed features of the environment and the soil. The accuracy and precision of mapping cannot be usually assessed from the report alone (Margules and Scott 1984).

Soil survey (free survey)

Description

The conventional form of soil survey is commonly referred to as *free survey* (Steuer 1961). It is suited to medium-scale or detailed-scale surveys and has been the method used for mapping in most developed countries. For example, most of the United States has been mapped at 1:20 000 or more detailed during the last 30 years. It was used widely by CSIRO and some state and territory agencies prior to the 1980s, particularly for the development of irrigated agriculture. Free survey has not been common in Australia since the late 1980s.

The steps involved in free survey are described in Table 18.2. Some important contrasts with integrated survey are as follows:

Table 18.2 The main steps involved in free and stratigraphic survey

Stage	Purpose	Typical activities
Planning	Define survey purpose and method	Consultation with those commissioning survey and agreement on the terms of reference (e.g. scale, target variables, study area)
Research phase (30%–50% of time)	Determine useful field relationships between soils and environment Devise mapping methods Characterise modal profiles	Air photo interpretation Transect surveys Stratigraphic relationships determined Develop legend (local classification) Detailed descriptions of selected profiles
Mapping phase	Delineate map units	Frequent augering and allocation of profiles to the classes of the legend using morphology
Independent validation phase	Test the predictive power of the map	Statistically based sample and measurement of selected variables
Interpretation	Relate map units to land planning and management	Detailed laboratory data are extended to map units defined by morphology (often implicit)
		Ratings of potential assigned to units
Reporting	Communication of results	Preparation of reports, maps and digital products

- much effort is devoted to the development of a local soil classification prior to mapping
- the primary purpose of the mapping is to draw boundaries; descriptions (and modifications to the local classification) are made later
- the local classification is related by correlation to other local classifications to ensure some consistency between surveys.

Strengths

- Free survey is efficient for soil and land survey at medium to very detailed scales.

Weaknesses

- The success of free survey depends heavily on developing good local soil classification; in some circumstances, this is not possible because the observable soil properties are not well correlated with attributes that influence land use (Butler 1980).
- The emphasis on classification influences mapping. Units are often portrayed as having sharp boundaries where, in reality, many soil changes are gradational rather than abrupt.
- Pedologists develop qualitative and complex conceptual models during survey. Unfortunately, the models are rarely communicated, and users of surveys find it difficult to separate evidence from interpretation (Austin and McKenzie 1988; Hudson 1992; Hewitt 1993; Webb 1994).
- Sampling, classification and mapping are subjective.

Stratigraphic survey

Description

One of the most notable developments in Australian field pedology was formulation of the stratigraphic approach by Butler (1958, 1967, 1982) and his colleagues (van Dijk 1958; Churchward 1961; Walker 1963; Beattie 1972). Similar ideas were developed in Africa and North America (Daniels et al. 1971). The approach places emphasis on the soil mantle rather than the profile. The soil mantle is more or less extensive in the horizontal plane and it has formed on bodies of surficial material or from the parent rock directly. The bodies of surficial material have been formed by erosion and deposition within the landscape. The stratigraphic relationships between the soil mantles provide evidence from which soil history can be deduced. In many Australian landscapes, this knowledge of landscape evolution and soil history provides a good basis for mapping and ensures a better appreciation of landscape processes.

The *paleosol* and *pedoderm* are central to stratigraphic work (see *Chapter 5*). A pedoderm represents one period during which soil formation has taken place (Beckmann 1984). Soil properties may vary across a pedoderm because of different soil-forming processes caused by variations in landform or parent material. Pedoderm *components* and *facies* (respectively) can then be defined. A component records differences in landform and lithology (e.g. floodplain and hillslope components). Soil facies are recognised where there are notable changes in pedologic features within a pedoderm; for example, because of drainage differences. A pedoderm can be subdivided into horizons, but pedologically related horizons cannot be considered as separate pedoderms (Brewer et al. 1970).

The system distinguishes soils on the basis of time, provenance, sedimentary system and drainage. It can be reconciled with the evidence of past events such as changing climates and widespread phases of erosion and deposition (see *Chapter 5*).

A hybrid approach with elements of integrated survey and the stratigraphic approach is the *soil materials approach* described by Atkinson (1993). It has formed the basis for most of the land resource survey in New South Wales during the last 15 years. *Soil materials* are defined as ‘three-dimensional soil entities which have both a degree of homogeneity and lateral continuity across the landscape’ (Atkinson 1993). A soil consists of one or more layers of soil material in succession. The layers may correspond with individual horizons or stratigraphic layers. Soil materials are defined and described morphologically and no account need be taken of its position in the profile and no assumptions are made in relation to formation. The soil materials concept has been useful for providing information on soil distribution and performance to users of surveys without having to involve complicated taxonomic terms. It has been useful in regions where soils have layers that are not genetically related (Chapman and Atkinson 2000). However, the approach does not prevent interpretations of genesis.

Strengths

- The stratigraphic system provides a general framework for developing detailed local accounts of pedogenesis that form a good basis for land evaluation (e.g. Butler 1967; Beattie 1972; McKenzie 1992).

Weaknesses

- The approach can really be only used in tractable landscapes. Difficult landscapes may not yield unequivocal field evidence because the stratigraphic record is incomplete or disturbed by later events. As a consequence, the soil–landscape model (exemplified by type transects and idealised sequences) does not make mapping easier.
- The fieldwork and skill required to define the pedodermis are considerable and may be beyond the scope of routine survey.
- The differences between pedodermis may be of pedological significance only.
- Pedodermis and related stratigraphic units may not have clear surface expression so mapping from remotely sensed imagery is difficult (e.g. Butler et al. 1973).
- It is difficult to represent three-dimensional stratigraphic sequences on maps without recourse to profiles.

Qualitative grid survey

Grid survey is most commonly associated with quantitative methods (see *Chapter 20*) but it has a long tradition in detailed qualitative surveys, particularly for irrigation development in flat landscapes. As its name implies, field sampling is based on a regular grid. In qualitative grid surveys, spatial extension of point observations usually involves manual interpolation to generate either land unit or isarithmic (‘contour’) maps of individual attributes. Qualitative grid survey is appropriate for intensive studies where air-photo interpretation is ineffective. For example, the surface expression of soil properties may be poor or complex in dense forests, extensive cleared plains and swamps. Grid surveys were once justified on navigational grounds in regions without reliable topographic maps – survey lines and distances between sites were used to locate the positions of sites. This justification is no longer valid with the advent of global positioning systems (GPSs).

Strengths

- The approach ensures even geographical sampling of the landscape.
- There is potential for statistical analysis.
- Survey can be done by staff with little experience.

- The approach is less prone to bias than other qualitative methods.
- The technique is successful irrespective of the terrain.

Weaknesses

- The approach is potentially inefficient, with excessive sampling in the most homogenous areas and too little where the soil pattern is intricate.
- Strict adherence to the grid can lead to delays in visiting sites in rough terrain.
- Possible bias can occur in landscapes with repetitive scales of variation (e.g. dunes and swales) that are either in or out of phase with the grid spacing (this is usually avoidable through sensible selection of the grid).

In its strict form, correlations between soil properties and readily observed landscape features are not used for delineating boundaries or generating isarithmic maps of individual soil properties.

Common features

Qualitative grid survey is considered further in a following chapter (see *Chapter 29*). The rest of this chapter concentrates on integrated, free and stratigraphic survey because they have common features. These methods use soil–landscape relationships as formulated in the mind of the surveyor as conceptual models. Together with supporting observations, the models are used to predict and map boundaries between land classes. Wherever possible, aim to declare these models in an explicit form through narratives, diagrams and rules.

The surveyor's understanding of the landscape evolves and improves during a qualitative survey. This increase in understanding occurs through an informal and iterative application of the scientific method: multiple working hypotheses relating to soil and landscape are formulated and tested, even though the deductive sequence is not normally subject to independent peer review and is rarely published.

No product from a survey completely captures or expresses the knowledge of the scientists involved. Maps, legends, databases, taxonomies, interpretations and reports are made mostly to meet the needs of users of information. Experienced practitioners have understood the underlying models, but they cannot convey it all in their reports. Moreover, few publications to date provide estimates of uncertainty in the results.

In these *Guidelines*, qualitative survey is divided into four phases.

- The *research or legend-building phase* where relevant information is collected at the outset and a structured reconnaissance of the survey area made. This produces a classification system with a mapping legend of soil or land types. This phase is often omitted from integrated survey.
- The *mapping phase* applies the classification system using remote sensing and field observation.
- *Correlation* ensures consistency of classification and mapping within and between surveys.
- *Validation* reports on the reliability of predictions.

Each of these will be considered in relation to the main forms of qualitative survey. Before this can be done, the different forms of sampling used in qualitative survey are described.

Sampling

Sample sites are often selected as 'typical' of either a district, land unit (e.g. soil type), or land management unit (e.g. farm paddocks or forest coups). This is *purposive sampling* and it is

efficient and logical when resources allow the soil at only one or two sites to be examined. However, it relies heavily on personal judgement and there is no way of knowing just how good that is. Results will be biased, usually with preference given to some part of the landscape at the expense of the rest. Bias is almost inevitable in human judgement, and it cannot be avoided either by training or by conscious effort (Webster and Oliver 1990).

Bias associated with purposive sampling can be reduced to some degree by planning and documenting all decisions. Purposive sampling should be supported by statements on the following:

- resources available for sampling
- scope of inference, target population and sampled population (see *Target and sampled population*)
- criteria used for stratification of the study region
- criteria for allocating samples to strata
- rules used for locating observations in the field (e.g. Petersen and Calvin 1986)
- areas excluded from sampling.

Seven broad strategies for purposive sampling can be recognised. A validation phase with independent sampling using a statistical method provides information on bias arising from purposive sampling (see *Validation*).

Convenience and informal sampling

Convenience sampling is easy, but it is the least satisfactory. Sites and soil profiles are selected because they are easy to reach: they may be existing exposures (e.g. road cuttings, stream banks, quarries) or readily accessed areas (e.g. public land, roadside reserves). Convenience sampling is biased. Roads are located to avoid particular parts of the landscape (e.g. wet land) and cuttings occur rarely in flat or depositional areas. Avoid convenience sampling – in most cases it is simply bad practice.

Informal observations across a survey area (e.g. general impressions, location of unusual features) can reveal significant features that require explanation and further investigation. View this information as a bonus rather than a primary data source.

Representative sampling

Integrated survey relies heavily on representative sampling. Sites are selected that are considered representative of the air photo pattern or landscape within a given land unit. Representative sampling provides data that will describe the land unit. It is also used during the research phase of free survey to construct the local classification for the study area.

Representative sampling is effective when done by a skilled observer with a full understanding of geomorphology, pedology and plant ecology. However, it is biased, and explicit rules for defining representativeness and the site-selection procedure are rarely prepared. The approach is less effective in cleared or disturbed landscapes because air photo patterns give fewer clues on landscape variation.

Free sampling

Free survey has two broad phases of sampling as noted in *Soil survey (free survey)*. The first usually involves representative sampling, often supplemented by convenience sampling, to develop a local soil classification. The second involves free sampling. The surveyor, armed with the local soil classification, traverses the landscape and allocates observed profiles to the classes. The surveyor locates map unit boundaries by making as many observations as possible in the allotted time. For this reason, data recording is kept to a minimum (i.e. see *Table 17.7* Level A where only the site location and name of the soil profile class are recorded).

recorded). More detailed observations may be recorded if adjustments to the local soil classification are needed.

The approach is suited to intensive surveys where many traverses by foot and vehicle are possible. Its effectiveness is determined by the quality of the local soil classification, the degree to which class boundaries coincide with observable landscape features and the ability of the surveyor. The main problems are potential bias and the collection from each site of a limited quantity of preclassified data. It is difficult to reuse the field data for other purposes.

Transects and gradsects

Soil properties vary along environmental gradients both past and current. Topographic and climatic sequences in particular are widely recognised (Birkeland 1999), and concepts such as the catena (Milne 1935) have been important in field pedology. Sampling at regular intervals along these gradients can reveal much about patterns of soil variation. It is efficient because the observer sees the range of variation with the least travelling. Gillison and Brewer (1985) formalised these notions in plant ecology through the concept of the gradsect.

Key areas

Nested sampling of key areas can improve the quality of the survey. Key areas are selected, usually on the basis of an initial reconnaissance and stratification of the region. These areas are then mapped in detail by either purposive or statistical methods. The aim of the sampling is to develop a reliable understanding of relations between soil and landscape features. This results in better appreciation of local-scale variation and more effective mapping across the broader region. Examples are provided by Thompson and Beckmann (1959), Favrot (1989) and Lagacherie et al. (1995).

Drawing from experience

Although not a formal strategy for sampling, surveyors undertaking a new survey often draw from experience gained in similar landscapes. This typically entails them using mental models of soil–landscape relationships to guide their sampling and mapping. At its worst, the approach uses narrow application of a preconceived model of soil variation and leads to a survey with poor predictive power. At its best, the approach (effectively sampling from another region) is efficient.

More formally, the approach has been implemented to extrapolate from surveyed to unsurveyed areas (Bui and Moran 2001, see *Chapter 26*).

The landscape detective

Butler's (1958) distinction between a geographical and a pedological focus manifests itself in a very practical way with sampling. Most of the approaches to sampling listed so far have a predominantly geographical focus. However, Butler's (1982) advice on how to undertake a district study was as follows:

it is best to start with an appraisal of the pedoderms revealed in river terraces and clay pits or gravel quarries in the depositional part of the landscape. Plateaux, the broader interfluvies and pediment terraces should also be examined for persistent pedoderms and aeolian sedimentation. These investigations would then need to be augmented by the judicious use of 10 cm auger and trench digging backhoe.

Other experienced pedologists and geomorphologists (e.g. Twidale 1976; Hall 1983; Daniells 1988) make similar recommendations. This approach to sampling involves the proposing and testing of multiple working hypotheses for soil and landscape evolution. Field operations then aim to find sites that refute or support particular hypotheses, and in this way the field operative

becomes a landscape ‘detective’. There is a degree of luck involved because some landscapes contain a rich record of landscape evolution (e.g. Bowler 2002), whereas others contain none.

While frustrating and opaque to the novice, the recommendations of Butler and others reflect a pedological focus: developing a chronology for soil development along with an insight into pedogenic processes. The primary result is a regional model expressed through a narrative, type sites, stratigraphic relationships, and in some cases, a generalised map. Field sampling by the landscape detective is often restricted to a few locations that are studied in great detail. The geographical focus, however, emphasises an even distribution of field sites (e.g. using representative or free sampling), and priority is given to the map and accompanying report.

Research phase

Qualitative survey depends on an inherent orderliness in the landscape (see *Chapter 2*). Orderliness is expressed in two ways:

1. as coherent relationships between soil classes and more readily observed landscape features
2. in the relationships between the soil classes used in mapping and the soil properties that are of interest to the user.

These relationships are investigated during the research phase in free and stratigraphic surveys. This phase is less clear in integrated survey and often it takes the form of a brief reconnaissance of the region. During the research phase, the surveyor builds his or her understanding of:

- the relationships between soil, landscape and environment
- the effects of scale on these relationships
- soil and landscape genesis.

The relationships formulated need to be open to scrutiny so other scientists can evaluate them and improve them or controvert them with new information.

Evaluate existing data

Begin by reviewing existing knowledge on the genesis of both soil and landscape, and relationships between land use and landscape attributes. Contact individuals with relevant field and theoretical expertise including geologists, geomorphologists, ecologists and pedologists. Identify information that might support existing models. It might be in the literature, implied in maps and map legends, or embedded in existing data.

Existing information will vary in availability, format and reliability. Increasing sophistication and use of metadata have permitted easier access and understanding of the potential use of data about natural resources. Most public agencies responsible for information on natural resources have online systems for metadata (ASDD 2006). Ensure you have the following if they are available:

- soil and land survey reports and maps (in paper or digital form)
- data sets on morphology, chemistry, physics, mineralogy, engineering and biology of the soil
- data from field experiments including fertiliser trials, plant performance trials, land management trials, ecological monitoring or research plots
- relevant taxonomies, including keys, definitions, and examples of allocated sites or profiles (e.g. soil profile classes, soil series, and other soil or land taxonomies)
- unpublished or incomplete surveys and survey data

- geology (reports, maps, geochemical data – see *Chapter 4*)
- geomorphic studies (chronologies, stratigraphies, process studies – see *Chapter 5*)
- topographic data (maps, digital elevation models and derived terrain attributes – see *Chapter 6*)
- climate station records and interpolated climate surfaces (see *Chapter 7*)
- vegetation surveys (reports, maps, plot data, species lists, local keys, process studies, accounts of vegetation history and responses to disturbance – see *Chapter 8*)
- maps of land use and land cover (see *Chapter 9*)
- reflectance-based remote sensing (e.g. air photography, satellite imagery – see *Chapters 10–12*)
- geophysical data (e.g. gamma radiometric spectroscopy, electromagnetic induction – see *Chapter 13*)
- landscape features (streams, lakes, human-made features)
- environmental surveys
- theses and research reports
- ‘grey’ literature including company data and unpublished material.

Nearly all land resource surveys now rely on GISs and relational databases to store, access and analyse data. Capture digital data early in the research phase. Follow the guidelines for survey operations (see *Chapter 16*) and ensure systems for information management satisfy the recommendations (see *Chapter 25*).

Checking and verification

Evaluate existing data for accuracy and relevance to the new survey. Initially this may involve your investigating accompanying metadata or associated documentation. In many cases field checking is necessary. Inaccuracy can often be accommodated if the nature of the uncertainties is clear.

Correlation with existing mapping

Identify maps of neighbouring regions and determine the need for matching boundaries with the planned survey. Try to correlate soil profile classes so that mapping and description are consistent between surveys. Correlation of new classes with existing mapping is a major task for survey organisations. New surveys often force revisions of existing concepts and classes.

Digital capture and data quality control

Digital capture from hardcopy of map, site and profile data can be expensive. Check that digital representations are faithful to the original. You might identify data errors by cross checking. For example, land system and vegetation surveys from the 1960s and 1970s frequently used common classifications so that the boundaries between classes matched. Overlaying within a GIS will enable comparisons to be made. If the maps have, as is usually the case, been digitised separately, use other sources of data also (e.g. rectified Landsat imagery). In many cases, there will be sufficient evidence to make corrections.

Extracting predictive models from existing reports and research data

Existing soil maps and reports display the results of the original authors’ reasoning but often do not adequately describe the reasoning itself. Sometimes you can decipher the latter from the resultant map and report by working backwards to deduce the thinking that led to the final product. For example, map unit boundaries that approximate contour lines evidently suggest that the surveyor used catenary relationships. The task can also be tackled statistically.

Provisional predictive model and stratification

Take the following steps to create a provisional predictive model and stratification:

- if possible, use terrain attributes (see *Chapter 6*) from a digital elevation model in conjunction with existing land resource maps to prepare an initial stratification
- prepare an initial interpretation of gamma radiometric spectroscopy, if the data are available
- examine classifications of imagery in relation to other spatial coverages (e.g. climate surfaces, land use)
- focus the exploratory analysis to prepare a mental model of soil–landscape relationships along with an initial stratification. Write it down and draw diagrams. This constitutes the provisional soil–landscape model that will be refined.
- ensure the provisional soil–landscape model will result in the relevant soil variables being satisfactorily mapped to the survey's objectives.

Specification of land properties required for survey outcomes

Most surveys are commissioned to meet specific objectives (see *Chapter 14*) in which certain properties of interest are defined in the terms of reference. It also defines the sampling scheme, mapping scale, design of map legend, and the degree of detail required for soil description.

The properties of interest to those who commission a survey frequently differ from ones that can be readily observed in the field – predictive relationships (pedotransfer functions) have to be applied or developed afresh. For example, irrigation design normally requires estimates of available water capacity. With a modest budget this can be directly measured at a few sites; elsewhere, available water capacity must be estimated from properties such as soil texture and horizon thickness. So, work back from the survey specification to the information needed for interpretations (e.g. of land suitability for various purposes) and then to the key properties that must be observed in the field. See *Chapter 22* for guidelines on existing pedotransfer functions along with principles and procedures for developing new ones.

The focus of soil survey is usually on soil properties that change very slowly with time. Although soil maps do not show the status of dynamic soil properties (e.g. those responding to land management), behaviour of such properties may in some cases be inferred from the more static ones. For example, the rate at which nutrients are moved by leaching may be inferred from the more slowly changing properties that control hydraulic conductivity. Predicting soil and landscape change requires more than a survey – modelling and monitoring are needed. See *Chapter 1*, *Chapter 28* (modelling) and *Chapter 30* (monitoring).

Relationship between soil properties and land surface features

Scale

Soil–landscape models need to be developed at a scale appropriate to the survey (see *Chapter 3*). In most landscapes, the properties that relate to the observed soil pattern change as survey resolution and extent changes.

For example, in mountainous terrain, variation in the organic carbon content of the soil at resolutions of a few metres might be related to patterns of past and present vegetation, erosion and grazing. But at a resolution of a few hundred metres, aspect may emerge as an important variable explaining variation in carbon – because it controls radiation and consequently soil moisture regime and net primary production. At a still coarser resolution – a few kilometres – the effect of orographic rainfall gradients may emerge as an important landscape variable controlling carbon. The variation may thus be nested, with total variation at coarser resolution recognisable over the ‘noise’ of the variation at finer resolution.

The soil patterns and landscape variables at finer resolution than the resolution being mapped may be recorded as part of the description of soil and landscape variation within land units. The soil patterns and landscape variables at coarser resolutions than the mapping resolution may be better recorded in associations of units that can be formally expressed as higher-level land units. Record soil patterns and related landscape variables at resolutions finer and coarser than the survey resolution to guide future sampling. The hierarchy of land units (see Table 3.2) provides a framework for dealing with scale in qualitative survey.

Initial landscape subdivision

Stratify the region into broad land units where particular sets of relationships seem valid – these units will normally be at Level 4 (*district*) in Table 3.2. Ensure that all land units at Levels 5 (*systems*) and 6 (*facets*) can be grouped unambiguously into these broader units. A good first approximation is to assume that soil–landscape relationships change wherever the factors of soil formation change (i.e. parent material, climate, landform, vegetation, time). Subsequent field work will refine the nature of the relationships.

Sample along environmental gradients

Use your knowledge of pedology to identify environmental variables that are likely to control soil variation. Plan transects (or some other cost-effective sampling scheme) to traverse the steepest environmental gradients. For example, if topography controls soil formation, then place traverses down slope across the range of gradients and aspects in the extrapolation domain. Data on land-surface features and soil properties are recorded at sites along these transects at frequent intervals.

The landscape features of interest are anything that will provide clues to the underlying soil properties. These range from landform elements such as concave colluvial footslopes that indicate deeper soils, to more subtle features, for example, halophytic vegetation that may prove useful indicators of salinity, or the colour of rabbit burrow spoil that indicates subsurface soil colours.

Sampling is most effective when a combination of strategies is employed. Use transects and gradsects, key-area sampling, draw from experience, and act as a landscape detective (see *The landscape detective*) during the research phase.

Building the soil–landscape model

The main objective is to recognise significant changes in soil properties or classes along sampled gradients. These might be revealed by simply graphing properties against environmental gradients, but more complex analyses are usually worthwhile (Butler 1980; Webster and Oliver 1990; see *Chapter 20*).

Two types of relationship are sought:

1. association between particular soil properties or classes and landscape features
2. spatial expression of these features.

These transitions, whether they are sharp, gradational, or occluded, need to be noted – they provide information for predicting the nature and placement of soil boundaries.

Wherever possible, take soil classes ‘from the country’ (Butler 1980; see *Chapter 19*). The process of developing local soil-profile classes proceeds alongside soil–landscape model development. Butler (1980) provides good practical advice on developing and testing classes.

Inevitably, there is a tendency for mental smoothing of observed relationships – the surveyor gives priority to observations that fit the emerging, or preferred, soil–landscape model and tends to dismiss observations that do not. Minimise this prejudice by recording

observations, analysing data, and summarising results. Because many observations are made in attempts to resolve a particular ‘problem of the moment’ in the field, the risk arises of uneven and poor sampling of the whole soil population across the landscape. A proportion of observations located with unbiased techniques is more likely to provide an accurate portrayal of soil variation and correlations with landscape features.

The soil–landscape models that underlie conventional surveys are conceptual. The surveyor creates them in his or her mind and expresses them in the map and legend. Unless the model can be communicated in a form that can be readily understood and applied by an independent person, then much of the knowledge that contributed to the survey will be lost (Hewitt 1993).

Soil–landscape relationships can be expressed in various ways, including narratives, cross-sectional diagrams, block diagrams and sets of rules. Graphical methods are presented in Chapter 32 and a set of rules is shown in Table 18.3.

Test and refine

Test the model at different locations in a similar landscape by comparing predictions against the results of field sampling. This sampling can be purposive or statistically based. Modifications to the model are made as necessary and retested. At this point, the utility of the broader units (i.e. land districts or land systems) can be evaluated. Check for conditioning variables: for example, relationships between soil and topographic position may change with increasing rainfall across a land district.

The emerging soil–landscape models will not be fully developed at the time the research phase passes to the mapping phase. The distinction between research and mapping is somewhat artificial since new data from mapping might reveal new relationships and help refine those already established. Continued modification to models will be necessary but, with time, they should become more stable although they will always perform better in some areas than others. The effort needed to improve models needs to be judged against budgets and the likely consequences of error.

Soil profile classes and map legend

As the study of soil–landscape relationships proceeds and the significant soil profile classes (see *Chapter 19*) are identified, pay attention to design of the map legend. The goal is to form mappable classes that are relevant to the survey objectives and to fit the landscape in a way that makes for efficient survey.

Soil profile classes

A soil profile class is a group of soil profiles that all meet the definition of the class of some soil classification system (see *Chapter 19* for a full account and definitions of soil phases and variants). The profiles are related by similarity of properties but are not necessarily related in space. A soil profile class is defined at any level of generalisation.

Land units

Land units define groups of soil profiles that are clustered in space and confined within a map boundary. The boundary is defined either by land surface features or soil observations or a combination of both. The profiles are related in space but do not necessarily belong to the same class of a soil classification system.

A land unit *type* appears on the map legend and comprises the set of all individual land unit tracts that share the same map symbol (see *Chapter 3*).

In free survey the first output from a soil–landscape model is a set of delineated land unit tracts with statements on the mixtures of soil profile classes within each. In integrated survey

Table 18.3 A rule-based soil–landscape model: an example from Conroy land system, New Zealand. The soil symbols (A–G) are defined as per Hewitt (1995) (see footnotes to the table).

Land elements	Soil symbol
A. Slopes of more than 12 degrees	
a. rock outcrops or rocky bluffs	RX ^A or Cn ^B
b. linear or concave talus slopes with angular boulders on the soil surface	Hbb ^C
c. shady slopes (aspect 90–200 degrees magnetic)	
concave profile	Hb ^D
linear profile	
nose slopes	Cn
slight nose or side slopes	Hb
hollow slopes	Hb
convex profile	Cn
d. sunny slopes (aspect 0–90 and 200–360 degrees mag.)	
concave profile or drainage hollows	Hb
all other slopes	Cn
B. Slopes 12 degrees or less	
a. fans issuing from gullies with sharp relief	RF ^E
b. other fans or terraces	Hb
c. valley floor floodplains	
without water-courses that flow every year	RF
with water-courses that flow every year	GR ^F
d. crests, convex or linear nose slopes, or saddles	
associated with rock outcrops, or that have angular gravel or boulders at the soil surface	Cn
that have bare ground with hexagonally cracked soil (hexagons less than 15 cm), white or pale yellow soil material exposed by erosion or rabbit burrows or white quartz gravel at the soil surface	Bk ^G or Ch
e. rock outcrops	RX or Cn
f. concave or linear, side slopes or hollow slopes	
that are more than 100 m from a rock outcrop or crest, or are below slopes that are 12 degrees or steeper	Hb
that are associated with tor land, fretted land or crests with outcrops	Cn
g. flat to undulating land without outcrops	Hb or Ch

Soil legend: RX^A, Undifferentiated rocky recent soils or rocky raw soils; Cn^B, Conroy soils; Hbb^C, Hawksburn bouldery soils; Hb^D, Hawksburn gravelly soils and Hawksburn stoneless soils; RF^E, Undifferentiated recent gley soils; GR^F, Undifferentiated recent gley soils; Bk^G, Becks soils; Ch^H, Chapman soils.

the delineations are given, and the approach is to discover their taxonomic content. In either case it is desirable to reduce the number of land units to some manageable number by grouping

tracts with similar compositions of soil profile classes to form land unit types. These are described in the map legend.

Designing the map legend

Helpful guidelines on legend design include Rossiter (2000) and Soil Survey Division Staff (1993). Decisions are needed on the following.

Size of map delineations

The size of tract is related to the complexity of the soil pattern and cartographic constraints. Where soil varies little and transitions are widely spaced, tracts may be large – there is no maximum size. Where the soil varies much over short distances, then the minimum sized delineations are constrained by the size that can be depicted at the publication scale. ‘Grains of rice’ mapping can be avoided by grouping adjacent delineations to form more-generalised land unit types.

Number of soil map units

A sensible number of map units will be found by balancing the consequences of defining too many or too few. Too many may cause undue confusion, may produce classes that are poorly distinguished, and may produce a map legend that is too complex. Too few will cause over-generalisation with loss of information. Remember that human memory or recall of phenomena is determined more by the number of categories in which they are grouped than by the breadth of the categories (Beckett and Bie 1978) – aim for 7 ± 2 classes at any given level of classification (see Miller 1956).

Scale and the hierarchical level of national classification

Soil profile classes ‘taken from the country’ will normally be allocated to categories of regional, national or international systems (e.g. Australian Soil Classification, World Reference Base). The level of allocation in these systems (e.g. order, suborder, great group or family) depends on the map scale and the degree of discrimination between mapped soils required by the soil survey objectives (see *Chapter 19*).

Nomenclature and map-unit standards

Where a land unit has predominantly one class of soil then it is a simple unit (a *consociation*). If more than one class dominates, then it is a compound unit. Compound units may be identified either as an *association*, where the location of constituent soils may be predicted from landscape relationships, or a *complex*, where the constituent soils cannot be predicted readily from landscape relationships. Soils of minor extent are *inclusions*. Those with contrasting properties that are of significance to survey objectives are *limiting inclusions* and others are *non-limiting inclusions*. See *Chapters 3* and *19* for standards for the definition of land units and soil classes at various levels of detail.

Mapping phase

The research phase results in interim legends and maps, and an increasing understanding of the region’s soils and landscapes. When done well it improves the efficiency and effectiveness of the mapping phase. Iterative testing and improvement begins, and this continues into the mapping phase. The mapping phase concludes with final legends and maps and, with the development of the surveyor’s understanding, a clearer concept and definition of what uncertainty remains.

Site selection

During the mapping phase, the surveyor makes field observations to:

- identify and describe soil and landscape features
- delineate and confirm geographical boundaries
- elaborate understanding of soil–geomorphic relationships.

Careful selection of sites will maximise information gain for the effort expended. No matter what the scale or purpose, you will need to choose how many samples should be taken, and where they should be located.

Strategies for sampling in conventional survey are outlined in *Sampling*. The mapping phase usually has elements of representative, free and transect sampling (in contrast to the research phase which has a strong emphasis on key area sampling, drawing from experience, and acting as landscape detective). Most fieldwork in the mapping phase of detailed soil survey is done by free survey (see *Free sampling*) and in integrated surveys by representative sampling (see *Representative sampling*).

Sound sampling improves confidence in observations and predictions. In qualitative survey, selection is an iterative process – preliminary information obtained from initial sites serves to condition further exploration. More intense observation and sampling will be needed where there is much diversity, and where hypothesised soil–landscape relationships are speculative, difficult to discern, or disproved.

In many qualitative surveys, provisional map units are delineated during the research phase. During the mapping phase, confirm both the location of boundaries and allocation of the mapped areas to taxonomic classes. Record data that describe the soil and landscape features associated with the geographical units. At the same time, further develop your understanding of soil–landscape relationships and keep testing hypotheses – this will improve the efficiency and quality of mapping. Do this using reflectance patterns and features in imagery that relate to the appearance of bare soil, distribution of vegetation, land use and management, landform and hydrological features.

If description and sampling were not costly, sites could be selected in every land unit tract; further observations could also be made to confirm or reposition soil and landscape boundaries. However, in most surveys, the size and number of map units will preclude this luxury and soil–landscape models will have to be used to predict attributes for each delineated area.

Field sites serve many purposes and these include the following.

- *Preliminary description of major types of soil and land.* Identify these using the obvious patterns in remote sensing. Select sites to be representative of the patterns. Replication may be desirable even in predictable areas in order to estimate average values or refine soil profile classes.
- *Minor types of soil and land.* In many surveys, contrasting zones may occupy relatively small proportions of the land area, but may nevertheless need to be observed for completeness, or because they are important.
- *Outliers, anomalies and intergrades.* It is usual to pay more attention to areas in the landscape where prediction is poor. Deliberately locate sites in zones where understanding is poor and soils just do not seem to fit the pattern. Consequently, much survey time is spent at the margins. The efficiency of free survey derives from the soil surveyor always directing his or her efforts towards the unknown parts of the landscape.
- *Prediction and confirmation sites.* As the survey progresses, knowledge and predictability will often improve rapidly, with the result that fewer and more cursory observations may suffice.

- *Boundary location sites.* Land unit boundaries are delineated mostly according to patterns on remotely sensed images, direct observation in the field, or according to a predetermined classification of the landscape (e.g. a mid-slope break where change in slope is gradual but significant). Many field observations confirm that these boundaries exist either at or near the break or at a defined distance on either side. You should use these sites to define the character of the soil boundary.
- *Representative sample sites.* Again, as the survey progresses, specific sites may be tagged as *representative, modal* or *interesting* and be described and sampled in detail.

During fieldwork, adapt sampling on the basis of new evidence. Discovery of an anomalous site may prompt further investigation, whereas success in prediction confirmed by observation may mean that similar sites may not need to be observed in detail.

Because purposive sampling involves selection of many sites that are atypical, the complete set of sites will be biased and this has many implications for later use of the data (see *Chapter 26*). Unfortunately, the purpose for which a particular site is selected or a sample taken is not often recorded. Therefore, state the reasons for selecting a site and record it in the soil profile database: listing the sampling strategy will be sufficient in most cases (e.g. purposive convenience sample, purposive free sample, random sample).

In the absence of statistical sampling, select modal profiles from a set of sites that lacks anomalies or outliers. Record the disparity between the profile and the mode for the class.

Standard intensities for sampling appropriate to different scales or types of survey have been set out (see *Chapter 14*). You will need to adjust these intensities according to local landscape diversity, but they do provide a general basis for costing and designing fieldwork in the mapping phase. If you are in doubt about the sample design, apply a broadly spaced grid to provide a minimal, evenly spread sampling intensity, and supplement this with additional samples at your discretion (Dent and Young 1981).

Field observations

During the mapping phase, various types of field observation are made. Regardless of the intensity or detail of observation, all site locations must be accurately georeferenced (see *Chapter 16*).

Detailed site and profile descriptions (i.e. see *Chapter 17*, Tables 17.9 and 17.10, Level C or D) are made to define and refine soil profile classes, and characterise representative profiles. Detailed descriptions may also be recorded to document anomalies or interesting features.

In most surveys, the majority of soil and site observations will involve recording an intermediate range of attributes (i.e. see *Chapter 17*, Tables 17.7 and 17.8, Level A or B). These attributes will include those sufficient to identify the site and profile according to preliminary or predefined classes, important deviations of the site and profile from modal or expected conditions, interesting features, and any specific data to inform interpretations for users.

Where soil profile classes are defined, observations may be made to confirm the allocation of a land unit tract to a land unit type, and to verify the surveyor's prediction. In this case, the observation is at Level A and need only identify the diagnostic criteria for the class. In many cases, the local classification will evolve during the survey. Wherever possible, sufficient information should be gathered at most sites to enable reallocation without the need for expensive resampling.

Finally, representative sites are often selected from the database of collected sites, and then revisited for more detailed description.

Mapping boundaries

Soil and landscape boundaries are mostly delineated during the research phase, and then confirmed during the mapping phase. In Australia, detailed observation of boundaries has rarely

been performed except in high-intensity surveys or in specific places in broader-scale surveys where investigations of the boundaries are useful for understanding soil–landscape relationships. The emphasis on describing the composition of land units has meant that few surveys include information on the character of boundaries. It is possible to record different types of boundaries (e.g. sharp or gradual) and depict them on maps.

Boundaries can rarely be followed along their length, but rates of attribute change and soil–landscape relationships near and at boundaries can be explored by careful selection of sites around boundaries (e.g. regularly spaced transects transverse to the boundary and some parallel). This allows definition of change and continuity.

Representative sampling is employed in integrated survey. Information on boundaries relies mostly on evidence from the land surface.

Correlation

Until 10–20 years ago, many surveys in Australia were poorly coordinated and diverse in purpose, method and scale (Beckett and Bie 1978; Gibbons 1983; McKenzie 1991). The process of ‘correlation’ used in some countries – where contiguous, standardised surveys have been completed across large regions – has not been used often in Australia. For example, in the United States, correlation involves defining and naming detailed taxonomic units (soil series) and then imposing these across the survey coverage. In Australia, some agencies have matched boundaries and ensured taxonomic consistency between surveys. It is then much easier to provide state-wide coverage and to contribute to the Australian Soil Resource Information System.

Most Australian surveys involve individuals or small teams, and surveyors have limited supervision. Consistency and standards are better supported where survey is undertaken by teams, with experienced scientists providing technical leadership. In this way, leaders supply continuity of experience across space and time.

It is essential that survey agencies appoint correlators. Team-leaders need to then make every effort to work with the correlator to specify the scope of the survey and reach agreement on concepts and standards. The type of land unit depends on the purpose and scale of the survey. It will also be dictated by local soil and landscape conditions (e.g. scale of variation).

The correlator and survey team need to agree on methods and protocols to define what ‘level of impurity’ is acceptable in land unit tracts, the breadth of soil profile classes and land units to achieve concordance with existing (or future) mapping at levels above and below in the hierarchy of land units.

The major challenge of correlation is the same as that in classification: the more general the classes, the less well they fit the landscape. A compromise is needed between the definitions of local classes that fit a particular landscape or study area well, and broader classes that are applicable over a wider area including adjacent or regional surveys. For broad-scale surveys (e.g. state, national, regional studies of large catchments), consistency is essential. In order to prevent confusion, named classes should have defined limits that do not vary from one survey to another. The more a land resource survey is used, the more soil-class names acquire local parlance. Wherever possible, avoid *ad hoc* redefinition of named classes.

Validation

Qualitative surveys can be very efficient because they rely on sophisticated conceptual models of soil–landscape relationships. Furthermore, the data supporting the models can come from a wide range of sources. The main problem with the approach has been lack of a routine

method for assessing how good a particular survey is, and in particular, whether the assumptions relating to covariance between soil attributes and landscape features are supported.

This problem is overcome through an independent validation by using a phase of statistically designed sampling to test the predictive capacity of the mapping. The most effective approach in any particular case will depend on the context of the survey, so seek advice from a qualified statistician. The general requirements for validation are as follows.

- Identify target variables, from map predictions considered to be critical to the success of the survey and that, at the same time, can be measured with reasonable efficiency.
- Collect a statistically based sample of the complete survey area (or particular areas) with either stratified random, multi-stage stratified random, or cluster sampling (see *Chapter 20*). In most instances, a sample size of between 50 and 200 sites should be sufficient.
- Prior to field work, prepare an explicit protocol for site locations that includes criteria for rejecting sites if they prove unsuitable (e.g. river channels, sealed roads, capped land).
- Undertake field measurement and, where possible, use different staff to those responsible for the original survey.
- Compare the estimates for the target variables derived from the land resource map with those derived from the statistically based sample.
- Compute measures of predictive success: for example, using the intraclass correlation (see *Chapter 21*, Analysis of variance), standard errors of prediction, contingency tables, graphs of predicted versus observed variables.
- Report the reliability of prediction in a form that can be understood by the user.

It will take several years before a body of evidence can be accumulated that allows one to gauge, across a broad range of landscapes in Australia, what level of predictive success is acceptable. However, evidence to date suggests that variation within conventional land units is often large (e.g. Beckett and Webster 1971; Wilding and Drees 1983; Burrough 1993), and soil properties have varying degrees of covariance. Furthermore, for a particular attribute, the proportion of variance accounted for by a land resource map can be very small (e.g. <50% and often <30%). The difficulty is that a large proportion of soil variation occurs over surprisingly short distances. The implications of these findings are still poorly appreciated by the survey community, let alone by users of land resource information more generally. Independent validation and statements of uncertainty are improvements, but more needs to be done to incorporate this knowledge into recommendations on land use and management. In summary, the merits of validation are as follows.

Potential strengths

- If the validation sampling phase reveals the expert judgement to be sound, then the method will be efficient and capture desirable aspects of qualitative and quantitative methods.
- Predictions of individual soil and landscape attributes are provided with an explicit statement of uncertainty.

Potential weaknesses

- Survey agencies have to allocate sufficient resources to the testing phase and be able to ensure complete independence of the validation phase – this may be threatening to individuals responsible for the initial mapping.
- The effort devoted to the validation phase could be put to good use in the research and mapping phases to ensure maximum return on investment. The client needs to make a decision on this trade-off.

- The survey agency will have to be resourceful and flexible if the validation phase reveals predictions to be poor. Such a result may be difficult to explain to clients unless careful planning and negotiation had forewarned them of the possibility.
- Additional resources will be required to undertake extra field investigations if the validation phase reveals predictions to be poor (unless the situation is judged to be irredeemable).

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Classifying soil and land

B Powell

Introduction

This chapter explains how to use classification beneficially in land resource survey. Isbell's (1988) recommendations have been updated. Numerical methods are considered in Chapter 21. Classification of soil and land serves several purposes, namely:

- to organise our knowledge
- to simplify
- to correlate information between surveys
- to communicate survey results (Isbell 1988).

Classification always involves compromises – because of the continuous nature of soil variation and the varying degrees of correlation between attributes. Classification is essential for conventional survey but less important in digital soil mapping. The utility of classifications can be judged informally by their capacity to be internally consistent, their ease of use, and their relevance to users. Successful classifications provide convenient names for soil or land types along with information on key attributes. Classification, when well used by an experienced surveyor, accounts for much of the efficiency in conventional survey.

Most of this chapter is concerned with soil classification. Guidelines on land classification (i.e. mapping) are addressed elsewhere in the *Guidelines* (see *Chapters 3 and 18*). Classification of regolith is more complicated because there are often many layers in deep profiles and their genesis is complex – the topic is considered only in brief.

Concepts

The term 'classification' is often used imprecisely. In practice there are three aspects.

- 1 *Taxonomy*: a broad term that can mean a system of classification, the practice of classification or the principles and rules of classification. In this chapter it means the third – the theory of classification.
- 2 *Classification*: is the development of conceptual classes using existing knowledge. A *classification system* comprises a list of classes, their definitions, and a structure in which the classes relate to one another.
- 3 *Allocation*: (or *identification* or *assignment*) involves placing individual specimens, profiles or sampling sites into pre-existing classes, usually with a key.

You will need to understand taxonomy as it relates to soil: Butler (1980), Moore et al. (1983) and Eswaran et al. (2003) provide good starting points. You will also need to know how to

develop local classifications (see *Chapter 18*) and how to allocate soils using, as a minimum, the Australian Soil Classification (Isbell 2002) and the World Reference Base (Driessen et al. 2001). These systems are discussed (see *Official classification systems*). Since the landscape continuum provides the context for classification, make sure you understand the concepts and their practical consequences (see *Chapter 2*).

Entity of classification

In soil surveys, classification of soil entities (e.g. profiles or horizons) can be distinct from classification of land. The distinction rests on how the entity being classified is defined. As explained in Chapter 20, the primary entity for soil is defined through reference to a *point* on the landscape. The operational definition of *the volume* used for defining this entity provides the primary data for soil classification. Although this may seem overly semantic, attempts to define a natural volume of soil for classification and survey (e.g. pedons, polypedons) have failed in both theory and practice.

Systems of classification that use only horizons, or horizons and profiles, were introduced in Chapter 2. Although systems that use only horizons have advantages, there is nearly always a need to refer to sequences of horizons in the field. The problem becomes most acute in the classification of regolith because the sequences of horizons, revealed by borings or exposures, can be very diverse.

Official classification systems

In Australia, two main forms of soil classification are used in conventional survey. Local classifications are developed using field data taken from the survey region. In contrast, official regional or national classifications describe the full range of entities occurring across large regions, but for a given local region they do not necessarily partition variation effectively.

Butler (1980) recognised the lack of concordance between local classifications and those at regional, national or international levels and termed it the *taxonomic hiatus*. It often causes confusion, but mismatches should be expected because the systems at the different levels serve different purposes. The local classification, by definition, aims to describe naturally occurring classes in a confined, usually small region, whereas the national classification, at least for the whole of Australia and even its constituent states and territories, allows the local class to be communicated in terms of pre-existing conceptual classes derived from past knowledge and experience across a much larger national territory.

The Australian Soil Classification system

National and international classifications are developed to classify the full range of entities occurring within a country or the world. The Australian Soil Classification (Isbell 2002) is the official system for Australia so use it for all relevant aspects of soil and land resource survey. Jacquier et al. (2001) provide a convenient interactive key and Isbell et al. (1997) outline the concepts and rationale of the system. McKenzie et al. (2004) provide an illustrated account with supporting soil data for more than 100 representative profiles.

The World Reference Base

The international system for soil classification is now the World Reference Base. Details of the system, including keys, representative profiles, maps and general descriptions, are provided by ISSS Working Group RB (1998a,b), Driessen et al. (2001), Deckers et al. (2003), and FAO (2006). A good working knowledge of this system is invaluable. Wherever possible, allocate soils to both the Australian Soil Classification system and the World Reference Base.

Other international systems

Until publication of the World Reference Base, the *de facto* system used in many countries and used for communication internationally by them was the US Department of Agriculture's Soil Taxonomy (Soil Survey Staff 1975, 1999). This complex system was developed primarily for the United States and, not unexpectedly, it failed to discriminate between important groups of Australian soils (Moore et al. 1983). For this reason, it is generally of historical interest in Australia unless allocations to the system are needed for scientific publications in American journals.

The aim of national and international systems is to impose order on information and encourage understanding of the variation in soil properties across vast extents. It is to enable people with first-hand knowledge of the soils of a region to tell those outside it what the soil is like. Classification systems are also a basis for extending the results of scientific research (agronomic experiments, forestry trials, hydrological studies) to other similar areas, although this presumes strong covariance between the differentiae used to classify a soil and the soil properties that influence experimental results.

Local classification systems

Local classifications are developed by surveyors during a survey, and the soil profile classes are 'taken from the country' (Butler 1980). Such classifications are commonly used for surveying soil, land and regolith and have the additional purpose of assisting mapping, because they form the basis for map units. They do not necessarily match the classes in a national or international classification.

The number of soil profile classes created in surveys becomes overwhelming when survey programs extend across large regions, states and territories. There is a need to correlate the many classes so that comparisons can be made between surveys and across larger regions. This function can be served by a national soil classification but there needs to be a program of review and updating so that information from new surveys is incorporated. Of course, compromise is inevitable, and natural modalities evident in one landscape will often be different in neighbouring regions – there is then no optimal place to make the necessary taxonomic chops (Butler 1980). Survey agencies in some states have found it necessary to create intermediate classification systems to meet the needs of land evaluation. These schemes (e.g. Schoknecht 2001; Fitzpatrick et al. 2003) occupy a position between local soil classifications (from individual surveys) and the national system.

Guidelines for local classification systems are presented (see *Guidelines for local classification*). However, a further consideration of taxonomic principles is required before then.

Hierarchical and non-hierarchical classification

Most national systems for soil classification are hierarchical. For example, The Australian Soil Classification System has several levels (orders, suborders, great groups, subgroups, families). The *Référentielle Pédologique* (Baize and Girard 1995) is an example of a non-hierarchical system. The World Reference Base has elements of both systems. The advantages and disadvantages of hierarchical and non-hierarchical systems for classification are explained (see Chapter 2). Non-hierarchical systems have theoretical advantages, but hierarchical systems have endured because they allow abstraction at various levels, assist memory, and facilitate the construction of keys for identification.

It helps to realise that variation in soil is very different from variation in plants and animals. It may be thought of as a reverse ordering. Unambiguous clustering of soil properties is evident only at the lowest level of classification and within restricted localities. In biological populations, genetic forces produce nested clustering at higher levels, intergrades appear at lower

levels and within restricted localities. The net result is that hierarchical classification is more successful in biology than in soil science (Webster 1968).

Genetic, general-purpose and technical classification

Much debate on soil classification centres on whether soil genesis can provide a framework for classification systems. Beckmann (1984) and Heuvelink and Webster (2001) provide insights into unresolved issues. The search for a fundamental 'natural order' in soil, and representation of this in classification systems, has been unproductive. However, most systems of soil classification still have an implied genetic element; for example the Australian Soil Classification (Isbell 2002) retained many aspects of Stace et al. (1968). New systems are justified and constructed almost solely on utilitarian grounds, yet they still aspire to be epistemologically useful, including for pedological understanding.

Fitzpatrick et al. (2003) describe several technical classifications from Australia. By definition, these special-purpose systems use a restricted set of differentiae and have narrow application. Some special-purpose classifications can be derived from general-purpose ones (Moore et al. 1983).

Choice of differentiae

The choice of differentiae in a classification system at local through to international levels is made for one or more of the following features of the attribute:

- shows a strong correlation with others
- is known or suspected to be relevant to the purpose of the classification
- is easily observed or measured
- the attribute has been included traditionally
- is of particular interest to the classifier (Moore et al. 1983).

Stable attributes are preferred as differentiae. In effect this means that emphasis is placed on subsoils or deep regolith rather than topsoils (usually A horizons), even though the latter may be more important in practical applications. Isbell (2002) uses important topsoil attributes extensively at the subgroup and family levels.

Field morphology alone is unlikely to be sufficient for classifying soil except where strong correlations are known to exist with soil properties that control land use and management. Soil properties with potential for differentiae have been listed (see Tables 17.2–17.5). When constructing local systems of classification, you should pay attention to attributes such as the size and character of the coarse sand fraction and patterns of segregations.

Monothetic and polythetic systems

Classifications in which divisions between classes are based on single features are known as 'monothetic' systems. Such discrimination is convenient for construction of keys, but it can result in similar profiles being allocated to different parts of the classification because they differ in one aspect only. Furthermore, specifying precise class limits (i.e. Butler's 1980 'taxonomic chop') is often not sensible given the precision of laboratory and field measurements. The remedy in national classifications systems is to cater for intergrades. Isbell's (2002) system does this within subgroups. For example, there are *sodic* and *vertic* subgroups for Chromosols, which indicate affinities with Sodosols and Vertosols, respectively.

The antithesis of monothetic classification is 'polythetic' classification. In a polythetic system each class is defined on several features, *no one of which is essential*. Such classes of soil are more in accord with natural soil variation than monothetic ones, and polythetic systems have other theoretical advantages (Webster 1968; Butler 1980). Allocating new individuals to

classes in them is a complex process, however. McBratney (1994) provides a numerical method for allocation to polythetic classes.

Guidelines for local classification

Classes in the Australian Soil Classification or World Reference Base are seldom, if ever, appropriate for surveys at scales more detailed than 1:250 000. Even at this scale, the classes are likely to be inappropriate in many parts of Australia. Therefore, use the guidelines in *Chapter 18* and take the classes from the country (*sensu* Butler 1980). These classes should later be allocated in terms of the Australian Soil Classification and World Reference Base. Where appropriate, relate them to classes defined in nearby surveys.

The depiction of the local soil classes in a map can be a separate activity from the creation of the classes but the process of mapping and classification generally go together in local surveys (see Butler 1980). Use the taxonomic and mapping units recommended in the following sections.

Taxonomic units for surveys

Use the following definitions from Isbell (1988) in soil surveys at scales of 1:250 000 or finer.

Avoid terms such as soil type, soil series and soil family. These have been used imprecisely and now cause confusion. Instead, use the name and concept of the soil profile class. This flexible concept is suitable for surveys at several scales.

The level of generalisation of a soil profile class can vary according the survey's scale, its purpose, and the number of observations. As a consequence, even in detailed surveys, classes can vary in their degree of generalisation.

Soil profile class

The *soil profile class* is defined in general terms. It is a group of similar profiles, defined at any level of generalisation, but as a rule the ranges of the differentiae increase as the classes become more inclusive. The variation in some features within the class is less than the variation between classes. Soil properties used to define a particular soil profile class will most commonly include some or all of the morphological properties described, together with selected laboratory properties. Define soil profile classes so the user is clear on the criteria used for differentiation. Specify the number of observations used to create each soil profile class. Finally, relate the soil profile class to regional, national and international classification systems as required.

Soil phase

The *soil phase* is a subdivision of the soil profile class based on attributes that have particular significance to the use of the soil. Any attribute, or combination of attributes, can be used to differentiate phases. By definition, the class limits for the soil phase must remain within those that define the soil profile class. Common criteria for defining phases include texture (sandy), coarse fragments (stony), slope, state of erosion, depth (shallow) and salinity.

Soil variant

The *soil variant* has one or more profile attributes clearly outside the range of any defined soil profile class; even so it has either too few profiles described for complete definition or it occupies a small area and is not considered appropriate for definition as a soil profile class.

Identify soil profile classes with local geographical names. Examples include:

- Burdekin soil profile class – abbreviated to Burdekin soil
- Burdekin soil profile class, saline phase – abbreviated to Burdekin phase
- Burdekin soil profile class variant – abbreviated to Burdekin variant brown subsoil.

Do not use words such as river, creek or mountain.

If a region is resurveyed at a finer scale, soil profile classes will be less generalised. Use different names for soil profile classes in these circumstances. Individual soil profile classes, phases and variants will most commonly be confined to a region covered by just a few adjacent surveys. Ensure names are registered with the relevant state or territory agency responsible for the region. Avoid a proliferation of classes through an orderly approach to correlation. Ensure local names are defined and registered by experienced pedologists who have worked across a wide range of landscapes. These pedologists (*soil correlators*) will contribute updates to regional, national and international classification systems.

Mapping units for surveys

In theory, taxonomic units at any level of generalisation can be used as mapping units but in practice this seldom occurs: however, soil profile classes do not need to be contiguous, even though a mapping unit nearly always includes several profile classes. A mapped unit is a part of the real world of soil as opposed to the conceptual class created by the soil surveyor. As a general rule, mapping units become purer (i.e. tend to have a larger proportion of any one soil profile class) as the scale becomes finer to accommodate more detail. For mapping units in conventional soil survey, use the following nomenclature defined by Isbell (1988).

Soil complex

A *soil complex* is a mapping unit with two or more kinds of soil (soil profile class, phase, variant) or miscellaneous areas (see below) that occur in such an intricate pattern that they cannot, at the scale of mapping, be conveniently separated as individuals. These different kinds of soil may occur in a regularly repeating pattern (e.g. some forms of gilgai microrelief), or there may be none. Name the soil complex after the dominant soils (e.g. Alpha–Beta complex).

Soil association

A *soil association* is a mapping unit with two or more kinds of soil (soil profile class, phase, variant) or miscellaneous areas that are generally associated in a regularly repeating and predictable pattern (normally not intricate) that is usually associated with recognisable landscape features. The components are often individually large enough to be separated cartographically on fine-scale maps. Although every delineated body of a soil association should have the same major components, their relative proportions may differ. Name the soil association after its dominant soil profile class (e.g. Alpha association).

Undifferentiated groups

Undifferentiated groups have two or more different soil profile classes that are conveniently combined because their land use and management are the same or similar. Generally, some common feature such as steepness, stoniness or flooding determines land use and management. Different phases of the same soil profile class are not recognised as an undifferentiated soil group.

Miscellaneous soil(s) and Miscellaneous area

Miscellaneous soil(s) is reserved for mapping units that can be readily delineated but because of lack of time or access it is not possible to define component soil profile classes. Name these units after a prominent or relevant feature (e.g. steep lands with Rudosols).

Miscellaneous area is a mapping unit having little or no identifiable soil. Common examples include badly eroded land, capped land (e.g. sealed roads, buildings) or rock outcrop.

Confusion has arisen over the definition and terminology for *soil* as distinct from *land* mapping units. The definitions above refer to soil mapping units. Use the terminology for land units (see *Chapter 3*) when mapping units are defined explicitly by a broader set of land attributes. For example, Thompson and Moore (1984) defined a soil landscape as a class of land in which the soil types bear a constant relationship to each other because they have formed on a repetitive pattern of landforms developed during the natural erosion of a single rock type or single complex of different rocks. The unit has a similar drainage net throughout and usually a characteristic pattern in the distribution of native plant communities associated with the soil–landform–drainage pattern. Northcote (1984) provided another definition for a soil landscape and it too is treated here as a land unit type rather than a soil mapping unit. Soil landscapes build on the concept of the catena, proposed originally by Milne (1935a,b), to describe lateral variability on a hillslope. He emphasised that each soil along a slope bears a distinct relationship to the soils above and below it, for a variety of geomorphological, pedological and hydrological reasons (see Birkeland 1999).

As for regolith, there is still no commonly accepted national or international system for classification, although Chan et al. (1986) proposed one with their regolith map of Australia at a scale of 1:5 000 000. This was updated by Pain et al. (2002) whose system defines 44 regolith types that can be combined with 64 landform types. The focus is on the classification of materials, unlike soils, where the emphasis is usually on profiles (sequences of materials). Pain et al. (2002) emphasise classification of landscapes rather than regolith profiles. Boundaries are drawn on the basis of landforms and the concept of the catena is implicit in the definition of *regolith toposequences*. These are groups of regolith types linked by their regular association with particular landforms. Use the classification system of Pain et al. (2000) for regolith sites and map units, but recognise that most of the theoretical problems facing soil classification are magnified when it comes to regolith, particularly in ancient landscapes with thick covers of materials, complex stratigraphies, and multiple phases of weathering.

Conclusions

Very many data are acquired in land resource surveys. For effective communication, the information and knowledge embodied in them must be suitably organised. A classification system's success will depend on its relevance and ease of use, and it can spur or deter interest and progress in the discipline (Fitzpatrick et al. 2003).

The state of classification systems is also a good guide to the scientific maturity of a discipline. In this regard, Moore et al. (1983) concluded 'there will always be some lag' between new information in classification systems and its application, and that 'the task of developing the ultimate classification is never complete'.

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Part 4

Digital soil mapping and pedometrics

Pedometrics is the science of applying mathematical and statistical methods to the distribution and genesis of soils. Here we consider only those pedometric methods of direct relevance to land resource survey. Chapters address statistical sampling, data analysis, functions for predicting soil attributes (pedotransfer functions), geostatistics, analysis of uncertainty, information management, and the emerging field of synthesis studies. Synthesis studies address methods that make the most use of existing land resource information.

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Sampling using statistical methods

NJ McKenzie, R Webster, PJ Ryan

Introduction

Sampling is the source of information in land resource survey, so choosing when and where to measure, and how to collect soil specimens, will determine a survey's usefulness. This chapter guides surveyors on sampling. It is assumed the client's needs and the survey's purpose are defined.

Sampling needs to be planned within the context of the complete survey, paying particular attention to how the data will be analysed. The complete plan is the sampling scheme, and it captures all the decisions and information for recording, observation and processing of data. A good strategy for planning the scheme is to start at the end and reason backwards (de Gruijter 2000). By gauging the precise needs for information, you will find it easier to plan a scheme that achieves the desired result efficiently.

Most sampling in Australian land resource survey has relied on expert judgement – statistical methods have been rare. The procedures have undoubtedly done the job but demands for quantitative information and estimation are making the approach outmoded (e.g. inability to predict functional soil attributes with accompanying objective estimates of uncertainty).

Sampling requires a clear and consistent conceptual framework. An essential starting point is specification of the soil entity and the population of interest.

Soil entity

Only a few soil properties can be directly observed at the surface. Most must be observed in profiles or by sampling at some depth, with material being taken from the field back to the laboratory for characterisation. The question is, therefore, where to sample.

Despite many attempts at definition, there is no natural volume of soil material akin to entities such as the organism in biological science. Soil forms a near continuous mantle and it can be viewed and characterised at spatial scales ranging from nanometres (e.g. clay mineral type) to thousands of kilometres (e.g. continental store of soil carbon).

Here we follow the conclusions of Holmgren (1988) and refer soil measurements to a certain geographical location (a point). The soil to be sampled is specified by operational criteria defining its lateral, vertical and temporal dimensions. It has proven useful for sampling and measurement to define soil horizons and profiles. The definition of soil horizons and layers is codified in the Australian Soil and Land Survey Field Handbook (McDonald et al. 1990). You will also need protocols to specify their lateral extent and thickness. This defines the soil volume that is characterised and sampled at each site, and here we refer to this operational entity as the *soil individual*. The protocols for soil individuals should not change during a survey program.

Support and georeferencing

The dimensions of the soil individual are determined primarily by the purpose of the investigation and logistic constraints. Most soil measurements involve the extraction of a specimen from the soil individual. The dimensions of the specimen define what is called the *support*. For a given soil, small supports will have more variation than larger supports.

Area of the soil individual

Unless there are strong reasons to the contrary (e.g. paddock-scale nutrient testing), the soil individual has an area 25 m by 25 m square that conforms to the Australian Map Grid. In landscapes with sharp boundaries, the 25 m by 25 m individual may be subdivided into 5 m by 5 m cells to improve resolution, or even 1 m by 1 m. Such subdivision, or stratification, will also be required when there are local patterns of soil variation (see Figure 20.1).

Locate sampling points and any relevant site boundaries to within 0.1 m, of their true position. Do this using a geographical positioning system (GPS) receiver (see *Chapter 18*).

The selection of 25 m by 25 m is somewhat arbitrary but derives from the following reasoning:

- it is broadly consistent with the resolution of current technology used for spatial extrapolation (e.g. digital elevation models with this resolution can be generated for many parts of the country)
- current global positioning technology can be used to locate the boundaries of the square with sufficient accuracy
- it encompasses common repetitive variation in soil (though not all gilgai patterns)
- it correlates with a volume of soil near the upper limit exploited by mature trees
- it is larger than has been the case in most soil investigations where short-range variation is usual
- it is of sufficient size for soil monitoring (see *Chapter 31*) – equivalent plot sizes are used for soil monitoring networks internationally.

Conformity to the Australian Map Grid ensures that the individuals are contiguous and mutually exclusive. While some other shapes have some small advantages (e.g. triangles and hexagons), squares are easy to lay out in the field.

The area of the soil individual is large as specified above, and only a few measurement technologies can integrate at this support. Replicated sampling within the soil individual and, therefore, estimation of relevant statistics are required.

In soil nutrient testing for agriculture, the use of the management unit – usually a paddock or zones within a farm – as the soil individual is well established, although the growth of precision agriculture implies that within-paddock variation can be managed (see McBratney and Pringle 1999).

Thickness of the soil individual

Placing a lower boundary on the soil individual is more problematic than specifying the area. Much of Australia is mantled by deep and often strongly weathered regolith. Most descriptions in soil surveys, field experiments and monitoring have been restricted to surface layers or an arbitrary solum (i.e. A and B horizons typically extending to a depth of about 1.5 m). This solum is not necessarily associated with the depth of root growth, and in many landscapes plants exploit deeper layers (C and D horizons).

The depth characterised might be limited by the equipment (e.g. soil augers or backhoe pits are often restricted to 1–2 m) or the purpose of the investigation (e.g. for agriculture the first metre or so).

You should characterise the soil to a depth where a root-impeding layer is encountered (e.g. lithic substrate, hardpan, watertable) or to where excavation is precluded by equipment. Reasons for a restricted depth of sampling should be recorded (e.g. standard procedure, lack of time, limit of equipment, coarse fragments).

Target and sampled population

The *scope of inference* of a land resource survey refers to the domain over which the results are to apply. It may be defined in purely geographical terms (e.g. local region, state, continent) or use other criteria (e.g. rainforest, crop lands, public lands). The *target population* refers to the aggregate of soil individuals that make up the scope inference. For example, if the scope of inference is Australia's crop land then the target population embraces all fields used for cropping. In contrast, the *sampled population* is the aggregate of units from which a *sample* or subset of units is selected for inclusion in the study (Cochran 1977; Olsen et al. 1999).

Ideally the target and sampled populations coincide, so statistical methods can be used to make inferences about the target population on the basis of the sample.

In order to meet your objectives, the sample population needs to be the same as the target population. This creates problems for land resource survey as well as for monitoring. For example, the criteria used to define crop land at the start of a monitoring program may become inappropriate if cropping practices change significantly during the study. By way of illustration, new cultivars may allow crops to be grown on more acid soils than before. Trends detected over time in soil acidity may reflect this transition rather than an actual change in soil condition for the target population.

A sampling frame needs to be defined so that the probability of selecting a soil individual can be specified prior to fieldwork – this is known as the *inclusion probability*. For example, in simple random sampling every soil individual has an equal inclusion probability, while in stratified random sampling there may be preferential sampling of some strata. Inclusion probabilities will therefore differ between strata but remain known. These principles apply to sampling within the soil individual and likewise at the regional level. Accurate location is essential in soil monitoring so that subsequent sampling is not on areas used previously. Accurate location also assists analyses where spatial registration with other data is required (e.g. digital elevation models, remotely sensed imagery). Real-time digital differential global positioning (RTDGPS) allows field location with submetre accuracy (see Chapter 18).

Sampling using statistical methods

The only sure way of avoiding bias inherent in purposive sampling is by *probabilistic sampling*. The theory is well established: see for example Cochran (1977), Yates (1981), Webster and Oliver (1990) and de Gruijter et al. (2006) for theory and computational formulas. These methods lead to estimates of population parameters without bias (e.g. means, variances) and to the degrees of replication needed to achieve sufficient precision. Such sampling is *design based*. In some cases, the spatial structure of soil variation within the soil individual or region will be of interest, and in these circumstances a *model based* or geostatistical approach will be more appropriate (see Brus and de Gruijter 1997; de Gruijter et al. 2006). While probabilistic sampling avoids bias, it can be expensive. There are many options for designing an appropriate sampling scheme and de Gruijter (1999, 2000) and de Gruijter et al. (2006) provide excellent guides. The following draws heavily from their accounts.

Random

In simple random sampling (Figure 20.1), all potential points in the survey region have equal probability of selection. Random numbers are used to generate the coordinates of sampling sites. Random sampling results in an uneven spread of sites with clusters and empty spaces. The estimation of parameters such as means, variances and confidence intervals is straightforward for quantitative variables. If indicator variables measured on binary scales are used (e.g. presence or absence of a pedological feature or soil class), then the formula for estimating the mean can be used to compute areal fractions.

While random sampling has an attractive simplicity, it is less efficient than other designs because the expenditure required to achieve a given precision is largest.

Stratified random

With stratified random sampling (Figure 20.2), the region is subdivided into strata, and simple random sampling is undertaken in each. Stratification may be based on a simple grid, existing land resource maps, landform, geology, vegetation, land management and distance from roads. The aim is to choose strata that are more homogenous than the whole region. Strata can be differentially sampled according to their importance for a given purpose (e.g. it may be important to sample lowland areas more intensively because of their significance for agriculture) or due to cost (e.g. areas distant from roads cost more to sample so it may be worthwhile to accept a lower intensity of sampling in these units).

Multistage stratified random

The region is divided into subregions (primary units). Sampling is then restricted to a randomly selected subset of these – this contrasts with stratified random sampling where every stratum

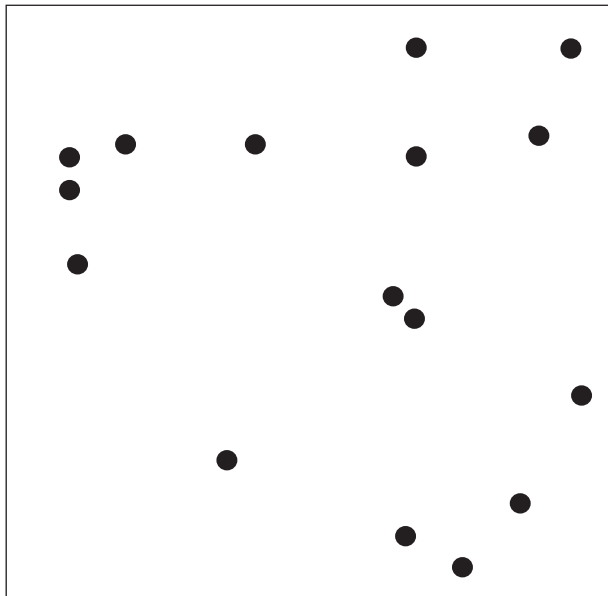


Figure 20.1 Random sampling (see de Gruijter et al. 2006 for details of computations for the estimated mean, variance, standard error and confidence intervals). Dots represent the location of the sampled soil individual.

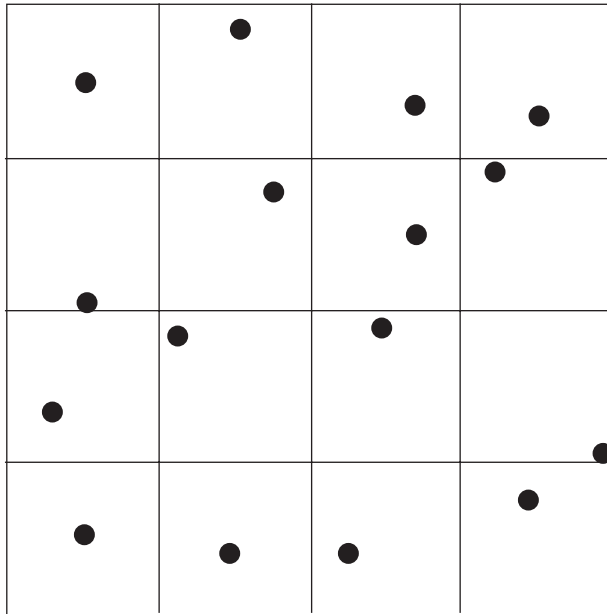


Figure 20.2 Stratified random sampling (see de Gruijter et al. 2006 for details of computations for the estimated mean, variance, standard error and confidence intervals). Dots represent the location of the sampled soil individual and the grid lines define the boundaries of strata.

is sampled (Figure 20.3). The method can be extended to have several levels of strata, hence the name, multistage stratified random sampling. As with stratified random sampling, sophisticated methods are available for optimising sample design for a given cost per site.

The clustering of sites within selected strata leads to economies in travel between sites. This advantage is enhanced if the primary units reflect access or cost of sampling.

It can be desirable to ensure that sampling is evenly spread through ‘environment space’ as much as through geographical space. For example, stratification may aim to ensure that equal sampling effort is devoted to landform classes (e.g. crests, midslopes, lower slopes) in different geological units and climatic zones within a region. The resulting spatial distribution of points may or may not be even – McKenzie and Ryan (1999) give an example of the approach while Latin Hypercube Sampling provides a formal framework (see *Chapter 25*).

Cluster sampling

Predefined sets of points (e.g. fixed-interval transects, or other configurations that suit the purpose) are selected rather than individual points. A random point is selected, and this is used as the starting point for the cluster. Clusters can be part of a stratified or multistage design (Figure 20.4).

Systematic sampling

In systematic sampling, the units observed are at regular intervals on transects or grids (e.g. Figure 20.5). Maximum precision is obtained from site locations at the intersections of an equilateral triangular grid because the maximum distance from unsampled to sampled points is least. However, square grids are more convenient and the difference in precision is small.

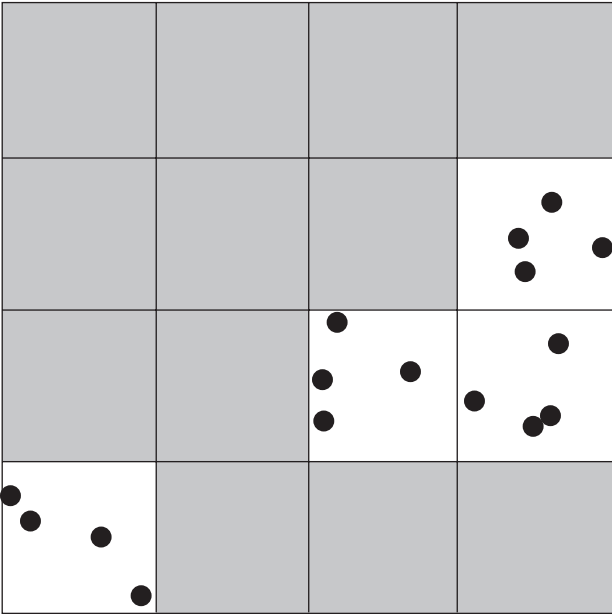


Figure 20.3 Multistage stratified random sampling (see de Gruijter et al. 2006 for details of computations for the estimated mean, variance, standard error and confidence intervals). Dots represent the location of the sampled soil individual and the grid lines define the boundaries of strata.

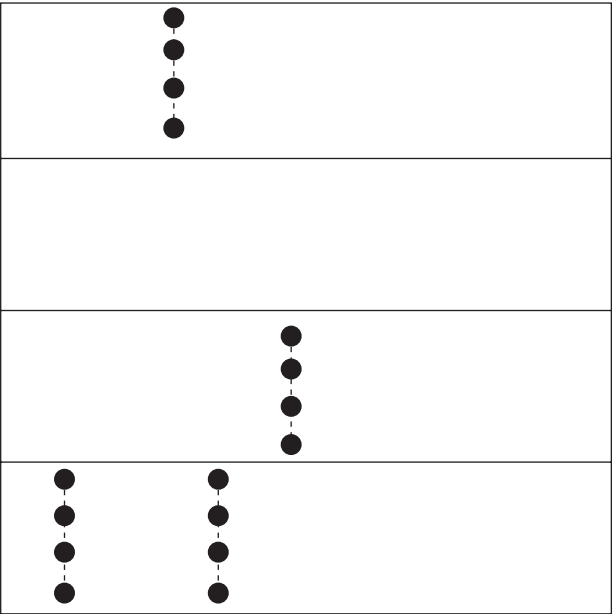


Figure 20.4 Cluster sampling (see de Gruijter et al. 2006 for details of computations for the estimated mean, variance, standard error and confidence intervals). Dots represent the location of the sampled soil individual and the grid lines define the boundaries of strata.

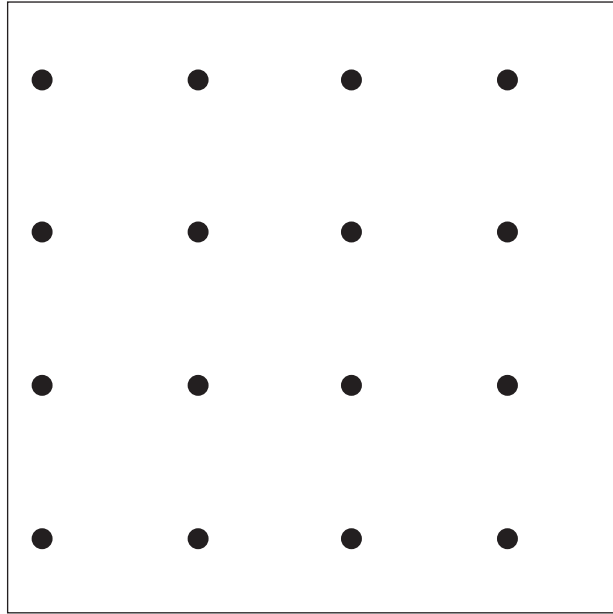


Figure 20.5 Systematic sampling. Dots represent the location of the sampled soil individual and the grid lines define the boundaries of strata.

The main disadvantage of systematic sampling is the lack of an unbiased method for estimating the variance and standard error of estimates. This is because once one sampling point is chosen, all the others are set. However, there are several approximate methods for estimating the variance with systematic sampling (see Yates 1981; Webster and Oliver 1990). Always check for periodic variation (e.g. gilgai, patterns of land use, dune-swale systems, bedding patterns in substrate) – this can lead to biased estimates of the mean and it becomes more of a problem when sample sizes are small. The problem can be avoided to a large degree through the use of unaligned sampling (Webster and Oliver 1990).

Other designs

Many combinations of statistical design are possible and they can be tailored to ensure efficient sampling of a landscape (see de Gruijter et al. 2006). Multistage designs are effective for determining scales of variation, and Pettitt and McBratney (1993) describe some useful strategies. Consult a statistician with a good knowledge of spatial statistics to help design a sampling scheme. Effective collaboration between the field scientist and statistician requires each to appreciate the theory and practice of the other's discipline – spend plenty of time discussing the sampling scheme and revising it where necessary.

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Statistical analysis

BL Henderson, R Webster, NJ McKenzie

Introduction

In soil and land resource survey the two main reasons for sampling and measurement are:

1. estimation of average values
2. prediction of particular values at unvisited sites, especially for mapping by interpolation.

Other reasons include discovering relations between and among variables, understanding landscapes and gaining insight into physical processes. This chapter reviews statistical methods in land resource survey. It sets the scene for following chapters on pedotransfer functions, environmental correlation, geostatistics and uncertainty. The reference list provides an entry point to the literature.

The main statistical techniques for survey are well established. They, together with the underlying theory and mathematics, are set out in many standard texts such as Webster and Oliver (1990; 2007) and de Gruijter et al. (2006). As it is impossible to repeat all the information here, the techniques most likely to be used are described briefly.

For your evidence to stand scrutiny and support your conclusions from survey you will need sound statistical analysis. If you yourself lack the expertise, or have any doubts about the propriety of an analysis, then consult a professional statistician. Perhaps even more important is for you to seek professional advice when you *plan* a survey and a sampling scheme. Many a survey has been rendered almost useless because the design was faulty.

Exploratory data analysis

A first step in analysing any set of survey data is to 'explore' it. This means to display the data as graphs, tabulate them, summarise them and generally 'get a feel' for them. This should help you to understand the data and explain them. It might lead to questions that you will want to pursue by statistical modelling. Exploratory data analysis should also identify mistakes and inconsistencies. The methods are fairly simple and elementary, but they are important.

Screening data

Good design, adherence to protocol and assiduous recording of observations should ensure that data from survey are of good quality and reliable. The protocol should have made provision for atypical conditions to be noted at the time of survey and records 'tagged' accordingly. However, despite the best endeavours, mistakes are made. So the first stage in exploration is to check the data for them. Screen the data for 'impossible' values, such as negative concentrations and

compositions that sum to more than 100%, site locations outside the region surveyed and transposed geographical coordinates.

If such values exist, decide what to do about them. This might mean scrutinising the laboratory records or field note-books for mistakes in transcription, or asking the laboratory to analyse samples afresh. If you cannot do either of these, then the only safe decision is to remove the records from your data.

Graphical methods

Simple screening as above will enable some mistakes to be detected, but there may still be others, values that are possible, but highly unlikely, in context. The next step in exploring data is to display them graphically. Graphing of data allows the view of its broad structure and distributional forms, and brings to light outliers, potential relationships and trends (Tufte 1990; Cleveland 1993).

Single visualisations can mislead – for example, they might show a relation between two variables simply because both respond to a third (unidentified) variable. To understand the emerging structure, it helps to view data in more than one way. There are many graphical techniques at our disposal.

Histograms and distributions

Histograms, density plots, boxplots and dotplots convey the shape of distributions. While these provide some view of the distribution, probability plots enable us to assess how closely the observed distribution matches a theoretical one. This knowledge can be important in validating statistical models that depend on distributions: for example, significance testing in regression modelling depends on the residuals being independent and identically distributed.

Outliers need even more scrutiny than ‘impossible’ values. They are not necessarily wrong. An outlier may be atypical but natural (e.g. chromium content of the soil over serpentine in an otherwise granitic landscape). It might arise from pollution, as happens where lead from dumped batteries has a concentration in the soil two orders of magnitude larger than the background. If the sampling sites were tagged at the time of survey with the relevant information, then these values would be readily explained and probably be correct. They will affect formal statistical analysis, and you need to decide what to do about them. The crucial question is: do they belong to the population that you are investigating? If they do, then you should include them and choose an appropriate form of analysis. If they do not, then you might remove them, at least temporarily, from the set of data. If you think that they are wrong, then, as with impossible values, you should do as advised above. The treatment of genuine outliers in data is a substantial subject in its own right; Barnett and Lewis (1994) describe it in depth.

What might appear as outliers at the long tails of skewed distributions need even more care. A Normalising transformation might show them to be no more than the tails of a Normal distribution. Many soil variables are approximately log-Normally distributed, and you should always examine positively skewed data by displaying their histogram when transformed to logarithms.

As above, a histogram shows the general shape of a distribution. If it looks approximately normal, then try fitting a Normal curve to it. If it is positively skewed with a single peak, then try fitting a log-Normal curve or transform to logarithms and fit a Normal curve to the histogram of the logarithms. You can also display the cumulative distribution on a normal probability scale. A Normally distributed variable plots on a straight line.

If a histogram has more than one peak, then almost certainly you have data from two or more populations, perhaps two or more classes of soil or histories of land use and fertiliser

practice. If you know to which class each observation belongs, then you can draw histograms and boxplots for each class separately and compare the diagrams visually (Figure 21.1).

Figure 21.1 presents, for pH data, some of these techniques used during the first National Land and Water Resources Audit (NLWRA 2001). Some 25 000 pH determinations from the surface horizon are displayed here and most derive from agricultural regions. The histogram, with an overlaid density plot, shows the overall distribution of pH data. The distribution appears to be bimodal and slightly skewed to the right. The strong non-linearity in the normal probability plot suggests that the distribution is non-Normal. The boxplots of pH show some clear differences. The often calcareous and semi-arid landscapes are reflected in high pH over most of South Australia. The surface soils of southwest Western Australia are more acidic, while the cooler and wetter climates in Tasmania also give low surface pH. Western Australia has many outliers and these may reflect areas where bases (e.g. Na^+ , Ca^{2+} , Mg^{2+}) have accumulated in the now largely semi-arid environments. Victoria exhibits a broad range between the

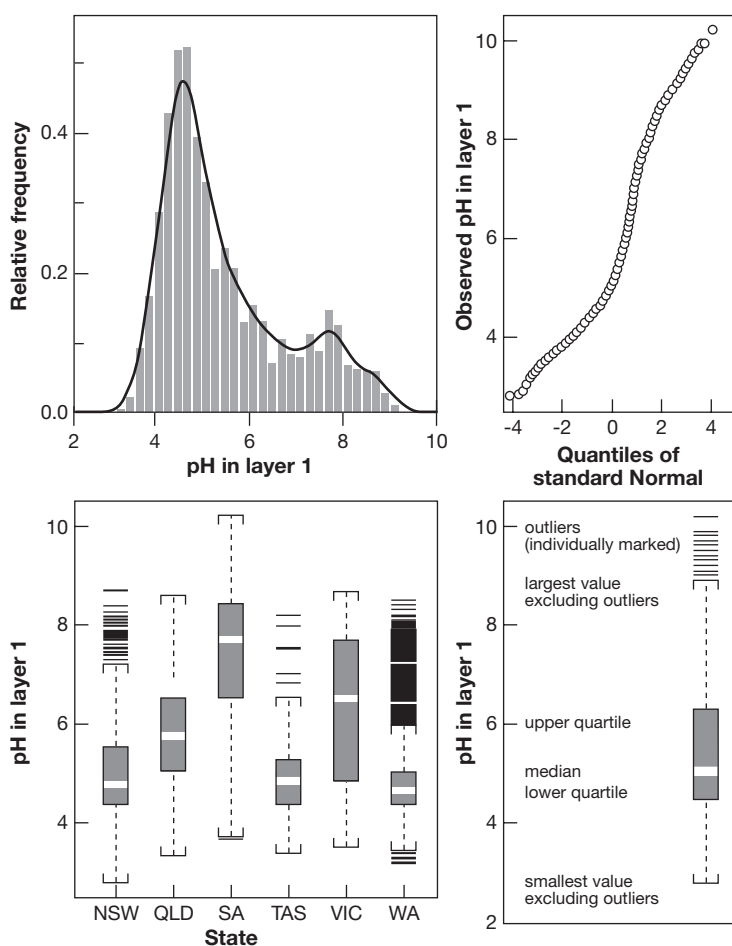


Figure 21.1 The pH data collated for NLWRA (2001): histogram and density plot, Normal probability plot, annotated boxplot and boxplot by state (clockwise from top left).

upper- and lower-quartile surface pH, and this is consistent with the diversity of climates and landscapes there.

Transformations

Transformations have three main objectives. The principal one for strongly skewed data is to stabilise the variances, especially for later formal analysis (see below and *Chapter 22*). Others are to achieve symmetry and so remove uncertainty about the centre of a distribution and make estimation more efficient than it otherwise would be.

Taking logarithms, either to base 10 or to base e , is one form of transformation. Other common ones are square roots (for data that are mildly positively skewed), logits and angular transformations. The logit transformation is often used for proportions that are constrained between 0 and 1, especially if there are many proportions less than 0.3 or greater than 0.7. Its formula (Equation 21.1) is:

$$y = \ln \frac{p}{1-p} \quad (\text{Eqn 21.1})$$

where p is the observed proportion. If all lie in the range 0.3 to 0.7, then the transformation has negligible effect and is unnecessary. Proportions that are based on counts, such as those of heavy minerals in samples of sand grains, follow a binomial distribution. For them you can use the angular transformation (Equation 21.2):

$$\phi = \sin^{-1} \sqrt{p} \quad (\text{Eqn 21.2})$$

Both the logit and angular transformations spread the distribution out towards the tails.

A more flexible transformation designed specifically to convert data to approximate Normality is the Box-Cox transformation (Box and Cox 1964). It includes the logarithmic and square root transformation as special cases. Its formula (Equation 21.3) is:

$$y = \begin{cases} (z^\lambda - 1)/\lambda & \text{for } \lambda \neq 0 \\ \ln z & \text{for } \lambda = 0. \end{cases} \quad (\text{Eqn 21.3})$$

You have to choose a value for λ to achieve the best transformation, which you can do from the data by the method of maximum likelihood.

Inference from statistical analysis often depends on assumptions of Normality, and you may think to apply a test of Normality to help you decide whether to transform. There are several procedures to test departures from Normality, but unfortunately they are of little help. Most of the commonly used statistical analyses are robust enough to cope with moderate departures from the underlying assumptions. See Webster (2001) for further guidance on transforming soil data.

Different transformations achieve different objectives. This is an inherent difficulty in choosing the best transformation (e.g. induce normality rather than create linearity) and it may be hard to find one that satisfies all objectives simultaneously. *Generalised linear models* (see *Statistical modelling*) overcome many of the difficulties associated with transformation by incorporating a link function and independently transforming the data, ensuring additive effects in the systematic part of the model and constancy of variance in the random part (McCullagh and Nelder 1989; Lane 2002).

Exploring spatial data

Spatial data should be scrutinised and summarised using all the criteria described above. In addition you will usually want to visualise their spatial distribution. This is best done with some congenial mapping program. Display the data by a 'posting' (i.e. a simple map showing the sampling locations) with the regional boundary drawn in. Any points lying outside the boundary are likely to be erroneous. Either their coordinates were incorrectly recorded or they

do not belong to the target population – unless they were deliberately sampled outside the region. Then, display the data with symbols that vary in size according their values (a ‘bubble’ map) or with varying colour from, say, blue for small values through the spectrum to red or purple for large ones. This may reveal spatial outliers (i.e. values that are markedly different from all others in the neighbourhood), even though they are not outliers in the marginal distribution.

If there is any strong trend across the region, such a map will show it. A weaker trend might be more difficult to detect, and if you suspect such a trend, you should explore it by trying to fit some kind of statistical surface by splines or regression. Spatial data are typically autocorrelated: observations that are closer together on the ground are more likely to be similar to one another than those further apart. Sample variograms or correlograms will generally show whether the data are autocorrelated at your working scale. Such correlation with no obvious trend leads into the realm of geostatistics (see *Chapter 23*).

At this stage you should not attempt formal modelling: rather the aim is provide you with a qualitative picture of the distribution.

A map of the data might show distinct patchiness in the distribution. If it does, then you should try partitioning the region into smaller subregions. It might be that these patches coincide, however approximately, with a traditional kind of mapping classification. You may then wish to analyse the data by soil class (see *Analysis of variance*).

Scatterplots and smoothers

If you have data on two or more variables, then you have further options for display. The most common and informative is the scatter diagram in which one variable is plotted against another, each unit being represented as a point on the graph. The scatter shows the general form of the relation between the two. If the points fall close to a line, then the relation is close. If the line is straight, then the relation may be treated as linear. If the points appear as a grossly inflated cloud, then the relation is weak and might not be worth exploring further.

You may incorporate additional variables by identifying groups on the graph using different symbols, for example, with with a size proportional to the magnitude of the third variable or with symbols to represent different classes.

Scatterplot smoothers can be useful in some instances, These are lines drawn through the scatter intended to reveal or summarise a non-linear relation that is not immediately evident in the cloud of points. Typically one of the variables is treated as the predictor and the other the response, as in regression. The smoother takes some form of local average in a window around the point of interest. The wider this window, the less local and smoother the line will be. Various smoothers are available: they include running means, lowess (‘**l**ocally **w**eighted scatter plot smooth’), kernels, smoothing splines, regression splines and natural splines, to name a few. Although all allow some control over the size of the local window, they differ in how they form the local averages. Hastie and Tibshirani (1990) and Green and Silverman (1994) describe some of these smoothers in detail.

Scatterplot matrices are useful when there are more than two variables. Two scatter diagrams are drawn for each pair of variables placed in a matrix. The names of the variables are entered in the main diagonal. To fit smoothers first one variable is treated as the predictor and then the other.

Figure 21.2 is an example of the scatterplot matrix for nitrogen (N), phosphorus (P) and organic carbon (C) data collated for NLWRA (2001), one for Queensland and the other for Western Australia. The same axes are used for both matrices to facilitate comparison. The figure shows a strong linear relation between N and organic C in Western Australia and a fairly strong one for Queensland. The relations between N and P are fairly strong in Western Australia

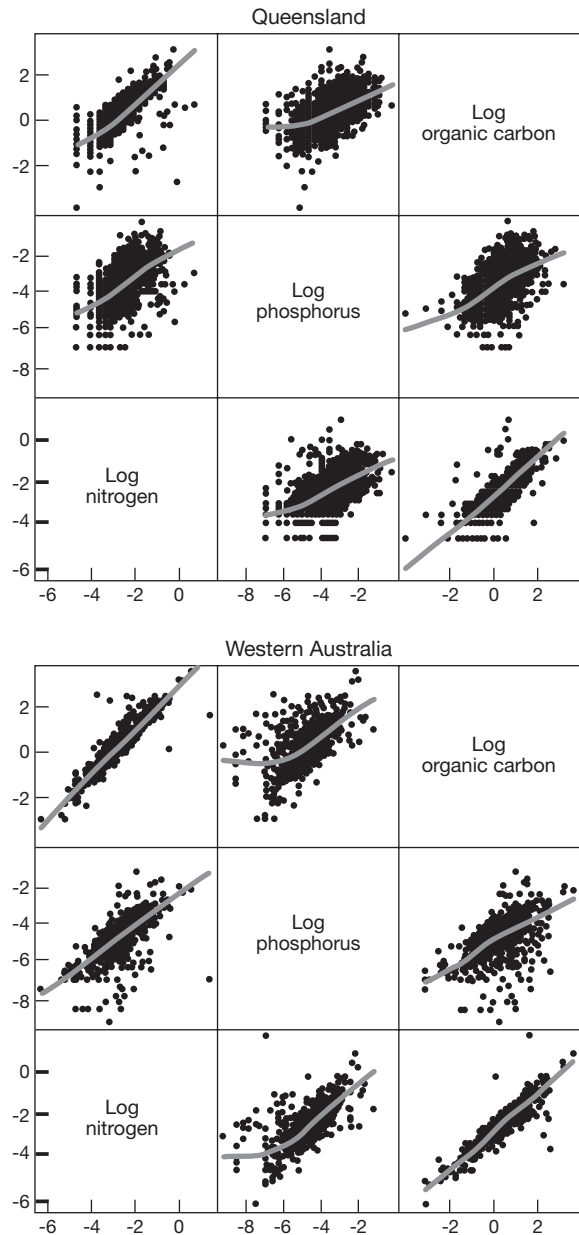


Figure 21.2 Scatterplot matrices for nitrogen, phosphorus and organic carbon conditional on state (a) Queensland and (b) Western Australia), with scatterplot smoothers (all on log scales).

and justify the lines drawn through the scatter. The other scatter diagrams show more inflated clouds of points (i.e. weak relations) and the smoothers are not very helpful. Note that all three variables are plotted as common logarithms.

The relations between any pair of variables can be affected by other variables, so there are complex interactions. You can discover such interactions using the *conditioning* plot or coplot (Cleveland 1993). Conditioning means that the data included in the scatter diagram

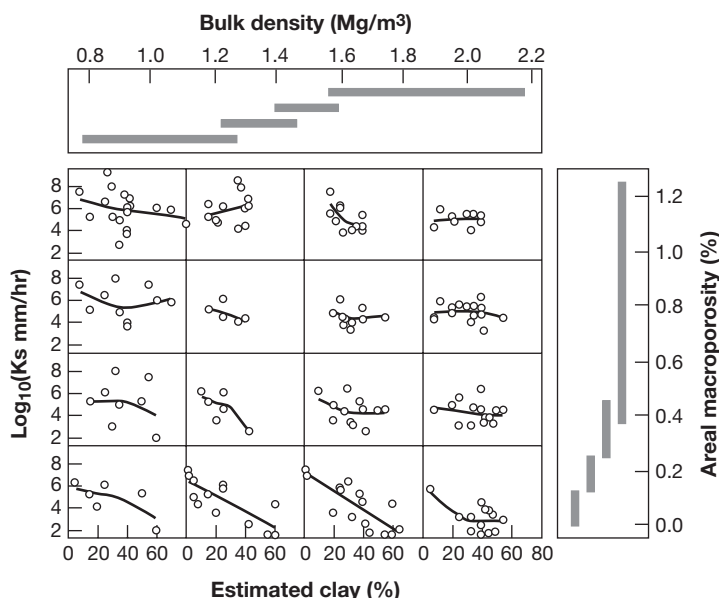


Figure 21.3 Conditioning plot of the common logarithm of saturated hydraulic conductivity ($\log K_s$) for 99 samples from a wide range of soils in southeastern Australia. The commonly held view that hydraulic conductivity is negatively correlated with clay content is valid only for horizons with moderate bulk densities (i.e. 1.2 Mg/m^3 – 1.6 Mg/m^3) and few macropores (i.e. 0% – 0.13%) – these conditions are displayed in the middle two panels in the bottom row.

are conditional on the values of one or more other variables. For example, the scatter of $\log_{10}K_s$, where K_s is the saturated hydraulic conductivity, against clay content recorded by McKenzie and Jacquier (1997) in southeast Australia appears as an inflated cloud with no clear relation between the two variables (Figure 21.3). If the data are partitioned into four ranges of bulk density and four of macroporosity, then some relations become apparent. Thus, there appears to be a negative linear relation between $\log_{10}K_s$ and clay content for bulk density in the range 1.2 Mg/m^3 to 1.6 Mg/m^3 and less than 0.13% macroporosity (middle two graphs in the bottom row of the figure). In other words, the flow is slower the more clay the soil contains. The third graph in the top row for macroporosity $> 0.4\%$ also shows a negative relation with clay content. The other graphs show only weak relations; in general, with greater macroporosity the clay content has little bearing on the flow. However, with only few points in each graph one would be well advised to treat these results with caution.

‘Three-dimensional’ scatter plots or point clouds are a popular way of visualising the data in three dimensions. Modern graphic tools on computers enable us to rotate, zoom and highlight subsets so as to identify structure in data. To explore more than three dimensions simultaneously, the number of dimensions need to be reduced in some way without losing important information. There are multivariate methods for this (see *Ordination*).

Summary statistics and tables

After the data have been displayed, you should next summarise them with descriptive statistics. The following are in common use; those printed in *italics* should always be computed.

- Central tendency: *mean*, median, mode, trimmed mean, geometric mean for positively skewed data. For N data, $z_1, z_2, \dots, z_N$ the mean is simply the arithmetic average (Equation 21.4):

$$\bar{z} = \frac{1}{N} \sum_{i=1}^N z_i. \quad (\text{Eqn 21.4})$$

- Dispersion: *variance*, *standard deviation*, minimum, maximum, range, interquartile range, coefficient of variation. The variance is best computed as (Equation 21.5):

$$s^2 = \frac{1}{N-1} \sum_{i=1}^N (z_i - \bar{z})^2. \quad (\text{Eqn 21.5})$$

The standard deviation is its square root.

- Other distributional characteristics: percentiles, *skewness*, kurtosis. The skewness coefficient, g_1 , can be computed from the third moment about the mean as follows (Equation 21.6):

$$\begin{aligned} m_3 &= \frac{1}{N} \sum_{i=1}^N (z_i - \bar{z})^3 \\ m_2 &= \frac{1}{N} \sum_{i=1}^N (z_i - \bar{z})^2 \\ g_1 &= \frac{m_3}{m_2 \sqrt{m_2}}. \end{aligned} \quad (\text{Eqn 21.6})$$

- Association between pairs of variables: Pearson correlation coefficient (product-moment correlation coefficient to give it its full name), Spearman or Kendall rank correlation. The Pearson coefficient between two measured variables y and z is defined as (Equation 21.7):

$$\rho = \frac{\text{cov}[y,z]}{\sqrt{\text{var}[y]\text{var}[z]}} \quad (\text{Eqn 21.7})$$

The Pearson coefficient is computed from sample data by (Equation 21.8):

$$r = \frac{\frac{1}{N-1} \sum_{i=1}^N (z_i - \bar{z})(y_i - \bar{y})}{\sqrt{s_y^2 \times s_z^2}} \quad (\text{Eqn 21.8})$$

where s_y^2 and s_z^2 are the variances of y and z , respectively.

If you transform a set of data, then you should compute the summary statistics on both the original and the transformed scale.

The above summary statistics characterise the data. If sampling has been random, then the quantities in *italics* estimate, without bias, parameters of the population from which the samples are drawn. Histograms can be turned into frequency tables, both for whole samples and for subsets.

The correlation coefficient, r , measures the strength of *linear* correlation. A value close either to +1 or -1 signifies a strong relation; one close to zero signifies a weak one. The word

‘linear’ is highlighted because there can be strong non-linear relations between variables for which $r \approx 0$. Note that correlation does not imply causation.

Frequency tables and cross-tabulations are valuable for showing distributions over classes and variables. Classes may be real (e.g. lithological classes) or constructed from existing quantitative variables (e.g. rainfall) as occurs with binning in a histogram.

Censoring

In many instances, observations on soil variables are incomplete in that they are known only to be less than some specified value or larger ones to be greater. For example, the cadmium concentration in the soil might be known to be less than the detection limit of the laboratory method, and the depth to mottling might be recorded as greater than 2 m because that was the maximum reached by the backhoe, or greater than 1 m because in a survey for agriculture, what lies below that depth is not very important to farmers. In other instances records might have been curtailed because rock prevented penetration below some depth. In all these instances the data are ‘censored’ (i.e. cut short). The result is that the frequency distribution does not fully represent the underlying probability distribution; one or other tail is absent. Hence, both the mean and variance of the data will be biased estimates of the population parameters. Special methods are needed to analyse such data – see Manly (2001).

Directional and compositional data

Some attributes of soil and land are directional and recorded on circular scales. Examples include aspect of sites and landforms, the orientation of cracks in the soil and colour hue. Special methods are needed for describing and analysing directional data (see Mardia and Jupp 1999).

Compositional data in which two or more variables sum to a constant, such as particle-size fractions that sum to 100%, also require special attention once you take the analysis beyond the exploratory stage. See Aitchison (1986) and Pawlowsky-Glahn and Olea (2004) for details.

Pseudo-replication

Replication increases precision of estimates by taking into account random variation. In a land resource survey N randomly selected sites might be chosen and duplicate measurements made at each site. If each observation is treated as a replicate, our sample size should be regarded as $2N$. However, the pairs of observations at each site would be *pseudo-replicates* of that site, and it ought to be expected that the observations are more or less strongly related to one another. This is not to deter you from taking measurements because there are good reasons to do so and you can, with the correct form of statistical analysis, expect to improve precision. See Manly (2001) for more on pseudo-replication.

Multivariate ordination and classification

Simple graphical methods such as scatter diagrams can reveal relations between pairs of variables, more elaborate computer graphics can show three-dimensional scatter, and with conditioning and clever choice of colour and symbols, more complex relations can often be identified. However, soil survey often results in data on many more variables usually with correlations among them and hence redundancy. Some way is therefore needed of reducing the number of dimensions while retaining the important information. The most important features need to be captured in a few new variables that can be visualised by graphing and characterising quan-

tatively. Classification is another way of simplifying data and thereby gaining insight into the variation (see *Numerical classification*).

Comparing soil horizons and profiles

A situation arises in soil survey that is poorly covered in statistical text books. It concerns variation among soil profiles that may be sampled at fixed depths or by recognisable horizons. If you choose to sample at fixed depths, you may treat each soil property observed as a set of variables, one variable for each depth. However, if there are marked recognisable horizons of varying thickness, this treatment is not necessarily the best. In such circumstances you might want to match the horizons in one profile with those of the same kind in others, regardless of their thicknesses and depths. Further, horizons present in one profile need not be present in another. The general problem is one of matching like with like, and there is no straightforward and universal solution.

You might want to overcome the difficulty by identifying some characteristic of whole profiles, such as the depth to maximum clay content, and compare those. More adventurous would be to fit a mathematical function of depth to data down profiles and compare those functions, as per Moore and Russell (1976). You might treat the profile as sequences (Norris and Dale 1971) or as arrays of layers defined by either depths or horizons (Rayner 1966; Moore and Russell 1976). These options are not part of the standard repertoire, and if you want to pursue them, then you should seek help of someone with the necessary understanding and expertise.

Ordination

There are several multivariate methods of analysis for the purpose and for which the term 'ordination' was introduced by ecologists. Of these, *principal component analysis* (PCA) is the most familiar. If one imagines measurements on p variables as a scatter in p dimensions, then one can think of PCA as rotating the configuration of N points rigidly to new axes such that the first axis has maximal variance of all possible axes, the second has the maximum variance of the residuals from the first axis to which it is orthogonal, the third has the maximum variance among the residuals from the first and second axes, and is orthogonal to them, and so on. The new variables are linear combinations of the original variables and are mutually uncorrelated. When the original variables are strongly correlated there is much redundancy, and a few new variables (principal components) will usually summarise the relations in the data satisfactorily and often reveal relations among both variables and units that were not evident previously.

You should transform any original variables that are strongly skewed so that long tails of distributions do not exert too much influence on the outcome. More seriously, you should realise that PCA can be done on any one of three matrices, the matrix of sums of squares and products (SSP matrix), say $\mathbf{S}$, the variance–covariance matrix, $\mathbf{C}$, and the correlation matrix, $\mathbf{R}$. The SSP matrix is (Equation 21.9):

$$\mathbf{S} = \mathbf{X}^T \mathbf{X} \quad (\text{Eqn 21.9})$$

where $\mathbf{X}$ contains data from which the means have been subtracted, and the superscript signifies its transpose. Matrix $\mathbf{C}$ is derived from it by (Equation 21.10):

$$\mathbf{C} = \frac{1}{N-1} \mathbf{X}^T \mathbf{X} \quad (\text{Eqn 21.10})$$

and matrix $\mathbf{R}$ is formed from $\mathbf{C}$ by (Equation 21.11):

$$r_{ij} = c_{ij} / \sqrt{c_{ii} c_{jj}}, \quad (\text{Eqn 21.11})$$

for all i and $j = 1, 2, \dots, p$. The last effectively standardises all the variates to mean zero and unit variance. The former two do not, and if you do a PCA on either of them, the variates with the largest variances will dominate over the others. You can avoid that effect by standardising the variates before you do the PCA. The output from a PCA includes the *eigenvalues* of the input matrix, the *eigenvectors* and the principal component scores.

Many packages list ‘loadings’. These may be the eigenvectors or the Pearson correlation coefficients between the new components and the original variables. Be sure you know what they are. You can display the correlations as scatter diagrams in the unit circle to show the relations among the variables. You can graph the scatter of the units to show their relations to one another. By judicious choice of scale you can draw ‘biplots’ that will show both sets of relations simultaneously (Gabriel 1971).

Plotting the scatter of the units in the planes of the leading principal components may reveal outliers that were not evident in the marginal distributions of the original variables. If you discover such outliers, then you should consider how they might have arisen. Have they some exceptional combination of values of the original variables?

PCA is essentially a way of transforming data so that you can explore them. It requires no assumptions about distributions. It is mathematical rather than statistical. It has, nevertheless, been used with remarkable success in many investigations in soil science. It reveals relations that might otherwise remain obscure and helps to create hypotheses about their causes.

PCA is one particular form of ordination. It is well suited to variables that have been measured on continuous scales. Many soil properties are recorded in other ways; some are binary (presence or absence), some are unordered multistate characteristics (e.g. type of structure), and some are ordered (i.e. ranked, such as degree of structural development). Straightforward PCA cannot cope with such diverse mixtures of scales, and more elaborate means are needed to represent relations in such data.

Whereas PCA analyses the relations between variables, other methods start by computing the similarities or differences between individuals (i.e. profiles or sites in soil survey). The differences may then be converted to ‘distances’ for display on graphs. Various measures have been proposed, but of these Gower’s general measure of similarity, which Gower (1971) devised for soil, is the most useful. It is defined as follows (Equation 21.12).

$$S_{ij} = \frac{\sum_{k=1}^p a_{ijk} w_{ijk}}{\sum_{k=1}^p w_{ijk}} \quad (\text{Eqn 21.12})$$

where a_{ijk} is a value for the comparison for the k th variable, and w_{ijk} is a weight assigned to it. For continuous variables (Equation 21.13)

$$a_{ijk} = 1 - \frac{|z_{ik} - z_{jk}|}{\max[k] - \min[k]} \quad (\text{Eqn 21.13})$$

where z_{ik} and z_{jk} are the values of the k th variable for the individuals i and j and $\max[k]$ and $\min[k]$ are the maximum and minimum values of z_k in the data, or ones known in the larger population from which the sample is drawn. For qualitative attributes $a_{ijk} = 1$ if $z_{ik} = z_{jk}$, and 0 otherwise. The weight w_{ijk} is conveniently set to 1 if the comparison for variable k is valid and to 0 if z_{ij} or z_{jk} or both are unknown or not applicable. The weight may be set to 0 for a binary

variable, k , where $z_{ik} = z_{jk} = 0$ and absence of the attribute is unimportant. The innovation was first used by Rayner (1966) and is now standard in programs such as GenStat.

Gower's similarity is readily converted to a 'distance' by (Equation 21.14):

$$d_{ij} = \sqrt{2(1 - S_{ij})} \quad (\text{Eqn 21.14})$$

Gower (1966) further showed that with similarities calculated as above it is possible to find the coordinates of the individuals relative to principal axes and so represent the data in a Euclidean space, as in PCA. He called the method 'principal coordinate analysis'. Webster and Oliver (1990) summarise the steps in the process.

There are many forms of ordination and a large literature is spread across many disciplines. Non-metric multidimensional scaling (NMDS) (Kruskal 1964; Kruskal and Wish 1978) has its adherents and it is less sensitive to non-linearity than PCA (Minchin 1987), principal coordinate analysis and the equally popular correspondence analysis (Benzécri 1973), 'reciprocal averaging' as it is called by Hill (1973, 1974). The idea behind NMDS is simple, but the computation is complex.

The analysis takes a matrix of dissimilarities and produces a configuration of points, one for each individual, in a nominated number of dimensions, in which agreement is maximised between the rank order of the distances in the configuration and the dissimilarities. The term 'non-metric' refers to the use of the rank order of the input dissimilarities in the construction of the configuration. McKenzie and Austin (1993) illustrate the technique with an example in soil survey.

Numerical classification

An ordination might show distinct clusters in the vector space of the leading new axes of a PCA or other analysis. If so, you might reasonably designate them as classes in a local soil classification. In practice, however, distinct clusters of soil profiles or sampling sites are rare. More often you see what appears as a single cloud of points. It may vary in density, and you might, therefore, wish the denser patches to form the cores of classes. In these circumstances numerical classification is another way of exploring relations in your data and with luck give you a useful tool at the end. Early methods of numerical classification, devised largely by numerate biologists, were hierarchical; they were intended to match the traditional classifications in plant and animal taxonomy. They had to be feasible in the computing environment of the 1960s and 1970s and they were essentially algorithmic. Pedologists tried to use the same methods for soil, but soon became disillusioned with them. Soil populations do not have a hierarchical structure. As computers became larger and faster, pedometricians were able to develop and adapt methods for non-hierarchical classification, and these have proved successful.

The basic method of non-hierarchical numerical classification is to create a set of k classes from the data such that there is no overlap between the classes in the vector space and some function of the within-class variance is minimised or the distances between the classes are maximised. This function is the optimisation criterion and needs to be specified.

In the original development, the user specified a set of k centroids (i.e. k sets of means) in the vector space of either the original variables or of new ones from an ordination. The units were then allocated to the centroids to which they were nearest and so became the *de facto* classes of the numerical classification. Units were then swapped between these classes or simply moved from one to another in attempts to optimise the chosen criterion.

Developments followed. For example, a whole classification could be presented to the computer program, which would then calculate the class means and improve the classification by moving units from class to class. Alternatively, the program could be asked to create its own starting classification. For investigators with little idea of the number of classes to request, the computer can be instructed to create a starting classification with more classes than finally desired, to optimise it according to the given criterion, and then to combine the two most similar classes, and to repeat the cycle of combination and optimisation until it reached some specified minimum number of classes.

Versions of the basic scheme are implemented in several standard statistical packages, including GenStat and S-Plus. You will find guidance in Webster and Oliver (1990) and Payne (2005), for example. The results of the method as described above are 'hard' classifications. Each unit belongs to one and only one class, and in principal there are sharp boundaries in the vector space between classes. Any new individual can be assigned to its most appropriate class with certainty. Several pedologists have questioned the wisdom of working in this way and have been attracted to fuzzy logic and its implementation in fuzzy classification. Fuzzy *k*-means classification is one outcome. In a hard classification the 'belongingness' of an individual is 1 for the class to which it belongs and 0 for all others. In a fuzzy classification it has a belongingness to every class, and this belongingness, say α , varies between 1 and 0. The larger is α the more strongly does the individual belong to that class, and the smaller is α the less strongly does it belong. The underlying idea is that this matches the pedologist's doubts about the allocation of individual profiles to classes and about soil classification in general.

Alex McBratney and colleagues in Sydney have been strong proponents of fuzzy classification and allocation (McBratney and de Gruijter 1992; Minasny and McBratney 2002; McBratney 1994; Mazaheri et al. 1995). There are several examples of their application in Australia (e.g. Triantafyllis and McBratney 1993; Triantafyllis et al. 2001).

Whatever technique you use you will reach a point where refining the method for numerical classification produces little gain or, worse still, leads to confusion between competing classifications. Thus, follow Webster and Oliver's (1990) advice that a 'sound philosophy is to be satisfied with what seems to be a good classification and to use it until it proves to be inadequate'.

The technology for numerical classification has reached the stage where it is useful in practice; it is no longer the preserve of research scientists. You have, of course, to have the sample data. A rough rule of thumb is that to create and define *k* classes requires roughly k^2 individuals. So for a single project in which you might want 10 classes you should have a sample of size 100. Obtaining that is feasible and should be affordable. Further, survey agencies should as a matter of course have the computational tools (programs) for it. The authors of this chapter advocate using numerical classification to define, or help to define, a local soil classification with the aid of ordination analysis.

Australia-wide the opportunities are fewer, if they exist at all. A national classification might have 100 classes, and, following the rule above, would require 10 000 recorded profiles to set it up. It would require a resourceful programmer to find a way of implementing the *k*-means technique to handle so many in reasonable time. More serious in a country the size of Australia is that the data do not exist for large parts of the continent. Improving national and international classification systems by numerical classification is a task for research organisations with national responsibilities.

Statistical modelling

The aim of statistical modelling is to reach a satisfactory understanding of those processes and circumstances that have led to the data observed. Although thorough exploratory data analysis can reveal trends, groups and outliers, statistical modelling is necessary if inferences are to be reliably extended to population characteristics and future data.

Arriving at a model is an iterative process. It often happens that the model initially selected is found to not satisfy adequately the required assumptions and is thus inappropriate. A refined model may then be produced, possibly requiring the collection and preparation of additional data. There are thus three phases to statistical modelling:

1. model formulation
2. estimation
3. model checking.

These phases are iterated until the model is found to adequately satisfy the assumptions made (Figure 21.4).

Many statistical models can be considered to be of the additive form:

$$\text{data} = \text{systematic component} + \text{random error}.$$

The two right-hand terms can be viewed as the signal and the noise respectively. Statistical modelling is chiefly concerned with decomposing the observed data into these two components. The systematic component is used largely as the vehicle for inference, whereas the

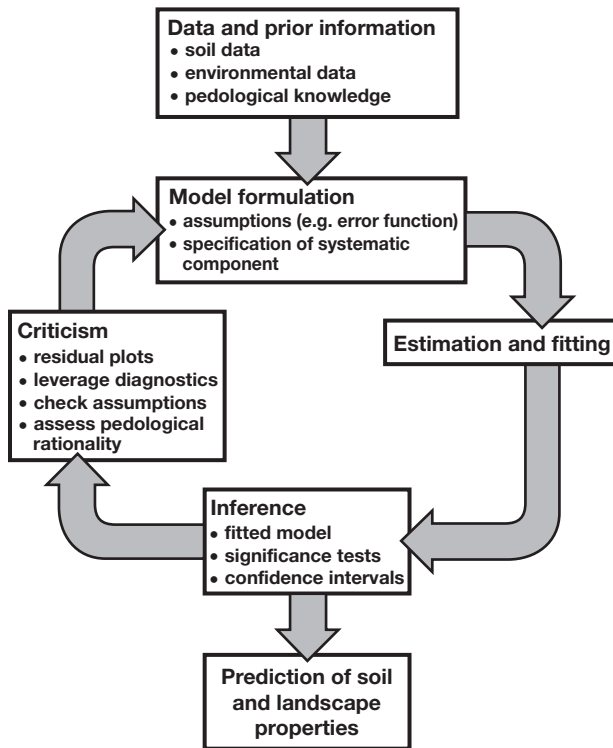


Figure 21.4 The process of model fitting (after Box 1979).

random error component is checked against the distributional model assumptions to assess the validity of the selected statistical model.

Analysis of variance

The analysis of variance is a basic statistical technique. It is commonly used to analyse designed experiments. It is also valuable for investigating the effectiveness of soil mapping (e.g. in the validation phase of conventional survey). The following is based on Webster and Oliver (1990) and their account, along with Webster (2007), should be consulted for further details.

Application of the method starts with a survey region, R , that has been classified into K classes separated by boundaries (e.g. land units). Every point in the region belongs to only one class. For any class in the region, the value can be expressed (e.g. soil pH, thickness, carbon content) of any point $\mathbf{x}_i$ selected at random (Equation 21.15):

$$Z_{ik} = \mu + \alpha_k + \varepsilon_{ik} \quad (\text{Eqn 21.15})$$

where Z_{ik} is the value of z at $\mathbf{x}_i$ in class k , μ is the general mean of z , α_k is the difference between μ and the mean of the class k , and ε_{ik} is a random component with mean zero and variance σ_k^2 , the variance within class k .

The mean of class k , $\mu_k = \mu + \alpha_k$, is estimated from n_k observations by (Equation 21.16):

$$\hat{\mu}_k = \frac{1}{n_k} \sum_{i=1}^{n_k} z_{ik} \quad (\text{Eqn 21.16})$$

with variance (Equation 21.17):

$$\sigma^2(\mu_k) = \sigma_k^2 / n_k. \quad (\text{Eqn 21.17})$$

If the sample is random (see *Chapter 20*), and μ_k is estimated by the arithmetic average above, the prediction variance, or expected mean squared difference (MSE), is (Equation 21.18):

$$\text{MSE}_k = \sigma_k^2 + \sigma_k^2 / n_k = \sigma_k^2 \left(1 + \frac{1}{n_k} \right). \quad (\text{Eqn 21.18})$$

A further assumption often made is that the variance within all classes is the same. This is a reasonable assumption for most surveys because mapping often aims to achieve this balance. This allows σ_k^2 in the above equation to be replaced by σ_w^2 , the average or pooled within-class variance. These quantities can be summarised in the familiar table for analysis of variance (Table 21.1).

The total variance in the region, σ_T^2 , can be written as (Equation 21.19):

$$\sigma_T^2 = \sigma_w^2 + \sigma_B^2 \quad (\text{Eqn 21.19})$$

Table 21.1 Summary table for analysis of variance of a survey with random sampling

Source	Degrees of freedom	Sum of squares	Mean square	F ratio
Between classes	$K - 1$	SS_B	B	B/W
Within classes (residual)	$N - K$	SS_W	W	
Total	$N - 1$	SS_T	T	

where σ_B^2 is the between-class variance. These quantities can be used to express the effectiveness of the mapping. Most useful is the intraclass correlation, ρ_i (Equation 21.20):

$$\rho_i = \frac{\sigma_B^2}{\sigma_B^2 + \sigma_W^2} = 1 - \sigma_W^2 / \sigma_T^2. \quad (\text{Eqn 21.20})$$

Clearly, the smaller the within-class variance and the larger the between-class variance, the more effective is the classification. Webster and Oliver (1990) provide more details. Experience to date suggests that qualitative surveys (see *Chapter 19*) can expect to account for about half the variance in physical properties of soil in most regions and considerably less for chemical properties (e.g. Beckett and Webster 1971). This is a sobering reality for soil surveyors.

Regression

Regression analysis is used to model relationships between a response and predictor variables. Classical statistical modelling assumes these relationships are linear. The term ‘linear’ (as in generalised linear models) is used in this book to refer to the *parameters* of the model – these form a *linear* combination (i.e. they can be added together). It does not imply that the relationship between the response and predictor variables forms a straight line. Curvilinear relationships can be modelled using a linear model (e.g. using polynomial terms).

Classical statistical modelling also assumes that the associated errors are independent and identically distributed with a common variance. Simple linear regression pertains to a single predictor variable, with equation $y = a + bx$, while multiple linear regression allows a suite of predictor variables to be included simultaneously. These predictor variables may be quantitative (i.e. interval or ratio), ordinal or nominal. Nominal predictors are included as factors, whereas ordinal variables are typically considered as quantitative if there are many categories, or nominal variables if there are only a few categories.

To ensure that the inferences made with the model are valid, it is important that the assumptions used are thoroughly checked. This requires detailed consideration of whether:

- the random errors are independent
- the assumptions of zero mean and constant variance for the random component are valid
- there is structure related to other predictor variables
- the residuals from the model exhibit departures from the assumed distribution (most commonly Normal).

More generally, the relationships between the response and the predictor variables may have one or more of the following forms or features:

- non-linearity
- exist over only a limited range
- non-Normally distributed errors
- an error variance that changes with mean (e.g. often a larger variance occurs with larger values).

Although transformations and the inclusion of polynomial terms may enable us to remain within the classical linear framework, they may make interpretation difficult and not always address non-linearity and heterogeneity simultaneously.

Generalised linear models

Generalised linear models (GLMs) are a natural extension for non-Normal distributions such as binary response or count data. Separate functions are used to relate a linear combination of predictors to the response (link function) and to model the mean–variance relationship (variance function). The choice of these functions affords us greater flexibility in accommodating non-linearity and mean–variance relationships in the modelling. The models include classical regression as a special case. Analyses such as contingency table analysis that were once viewed as distinct procedures also fall within the GLM framework. The framework reconciles many apparently separate statistical models and traditions of analysis into a single system with a common notation and unified estimation procedure. McCullagh and Nelder (1989) cover the subject, while Manly (2001) and Lane (2002) provide more accessible introductions. The models can be fitted to data by procedures available in several packages (e.g. S-PLUS, GenStat and glimR).

Probably the greatest benefit provided by the GLM framework for land resource survey is the integration of a former range of procedures for analysing categorical data (i.e. binary, ordinal, nominal data) and relating these to familiar methods for analysing continuous data (i.e. least-squares regression with Normal errors).

Generalised additive models and non-linear models

Generalised linear models are further extended to *generalised additive models* (GAMs – Hastie and Tibshirani 1990) by allowing additive terms in the linear component of the model to be arbitrary smooth functions. These models are sometimes termed semi-parametric as the form of these smooth functions is not prescribed parametrically but by the data. In any GAM, there may be a mix of terms entering as linear and smooth functions of the predictor variables.

Non-linear models are an alternative framework within which to address non-linearity in the data. Unlike GAMs – which relate the mean response to a linear combination of data-determined smooth functions of predictor variables through a specific link function – non-linear models are parametric, require complete specification of the functional form, and incorporate the parameters in a non-linear way (see e.g. Ratkowsky 1990; Pinheiro and Bates 2000).

Classification and regression trees

Tree-based methods are a popular modern alternative to GLMs and GAMs for regression and classification problems. Breiman et al. (1984) introduced tree models into the statistical mainstream from social science and machine learning. They remain the basis of many data-mining algorithms.

In a simple implementation, tree models use the predictor variables to partition the predictor variable space recursively so that each partition is increasingly homogeneous in its class (classification trees) or numeric response (regression trees).

Some of the popularity of tree models derives from them being computationally fast, able to cope with both quantitative and categorical predictors, are unaffected by a monotonic transformations of any predictor (e.g. log transformation) and can automatically handle interactions. The hierarchy in tree models may also be used to create a series of rules upon which predictions are based. For small trees, these can often be readily interpreted, but large trees are usually too detailed to offer a simple interpretation.

In practice, the tree is typically over-fitted and simplified (pruned) to something more stable. This is best done by the method of cross-validation. Model checking diagnostics, such as residual plots, are used analogously to those in traditional regression.

Tree-based methods have been used for several applications in Australian land resource assessment. They include spatial prediction via environmental correlation (e.g. Gessler et al. 1995; McKenzie and Ryan 1999; Henderson et al. 2001), salinity investigations (Evans and Caccetta 2000), and for the development of pedotransfer functions (e.g. McKenzie and Jacquier 1997).

Despite their apparent simplicity, tree-based methods should be used with caution. Data that lack a strong hierarchical structure will present difficulties. Likewise, if you rigorously apply diagnostics and cross-validation you will end up with a severely pruned tree. Large trees derived from big data sets can be overwhelming and difficult to interpret. Tree-based methods are probably most useful for exploring data. The structure in a data set revealed by a tree-based method can then be used to guide the selection of GLMs or GAMs.

Robust and geographically weighted regression

Unusual or outlying observations can excessively sway the regression process. Nevertheless, models that fit all the data except for a few outliers can reveal important structure. One approach is to omit outlying data from the analysis. An alternative is to employ robust techniques that are more immune to outliers. Such techniques retain observations that are far from the norm but minimise their by reducing their contribution to the distributional or regression parameters of interest. Rousseeuw and Leroy (1987) describe a series of robust regression procedures.

The literature contains other statistical modelling techniques for predicting soil properties from more readily observed environmental variables or related soil measures. See Hastie et al. (2001) for an excellent account of modern regression and classification techniques.

Fotheringham et al. (2002) outline regression methods for analysing spatially varying relationships. Their method of geographically weighted regression appears to have considerable potential in land resource survey but only a few applications on this topic have been reported to date.

Bayesian data analysis

The Bayesian paradigm represents a different and increasingly popular framework for statistical analysis. Parameters are estimated by combining of data with prior knowledge about those same parameters. The appeal of Bayesian modelling is that inclusion of this prior knowledge improves the estimates and thereby makes use of expert opinion. If you lack such knowledge, you may still select priors without any adverse consequences.

This is a powerful methodology as models can be formulated even for diverse problems. Most solutions require simulations, and appeal to *Markov chain Monte Carlo* (MCMC) methods (see *Chapter 24* for guidance). Lee (1997) provides more information on the Bayesian philosophy of data analysis and Jensen (2001) describes Bayesian networks and decision graphs. An application of Bayesian methods to environmental correlation and spatial prediction of soil properties is provided by Cook et al. (1996).

Some remaining statistical issues

Selecting predictor variables

Parsimony is a virtue. A parsimonious model describes the data well, excludes extraneous variables, and is relatively simple in structure. But there is always a compromise. As more parameters (variables) are included, a model will better predict the observed data. Yet if too many parameters are included, the model will not reduce the complexity and may not generalise well to new data. The fundamental trade-off is between bias and variance. If a model is underfitted, it will be biased but have low variance, but if it is over-fitted, there will be low bias but larger variance and less stability.

Use expert knowledge about physically important variables whenever you can. For small numbers of predictor variables, it is often possible to consider all subsets of variables and select the model that performs best. If there are many variables, and thus many candidate models, it is more important to be parsimonious and omit unnecessary variables. There are automatic variable selection procedures available. Some of these include or exclude variables in a stepwise manner; others consider a specified range of possible subsets. Selection of the best model is made on criteria such as adjusted R^2 , Mallows' C_p or the Akaike information criterion (AIC). All are based on some function of the model error (e.g. residual mean square) that is penalised by the number of the variables included. More on these procedures may be found in Miller (1990).

Assessing the reliability of models

Statistical models are simplifications of reality. In assessing the performance of any model, recognise that using the same data for model construction and testing will naturally lead to an optimistic and biased assessment of performance. This is because models are typically selected so as to maximise some criterion for goodness of fit. This is especially true for overfitted models where there are many variables (parameters) relative to the number of observations.

An unbiased validation of model performance can only be obtained with independent data. Such data might not be available and, if so, then randomly subdivide the data you have into training and test sets, construct the model with the training data and assess it with the test data.

Cross-validation is a generalisation of this training and test split, where data are partitioned into subsets. Performance is established by sequentially withholding one partition, constructing a model on the remaining partitions, and assessing the performance of the constructed model on the withheld partition. Averaging performance over each withheld partition yields a measure of model performance by cross-validation. The bootstrap and Monte Carlo methods involve resampling and they provide standard errors and an assessment of performance (see *Chapter 25*).

Use the correct measure of performance for predictive models. Although R^2 is often reported as a single measure, it is fairly crude because of sensitivities to the range of the predictor variables, to extreme values and to transformations of the response. Assess performance by the magnitude of the prediction standard errors. A goal for land resource surveys is to provide predictions of all relevant attributes with a stated accuracy and precision.

Very few surveys have used statistical sampling, and so reliable testing has not been possible. These *Guidelines* encourage qualitative and quantitative surveys to have an independent and statistically-based validation phase to estimate survey reliability (see *Chapter 18*).

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Predicting soil properties using pedotransfer functions and environmental correlation

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Introduction

At its simplest, a pedotransfer function converts one variable into another. Typically, such functions are used to translate available data into needed information. In most situations, there are environmental data (e.g. remote sensing, digital elevation models) and basic records on soil morphology, soil classes and standard analytical data, while the information really wanted is often more laborious or expensive to obtain (e.g. spatial predictions of hydraulic properties, nutrient supply characteristics).

Pedotransfer functions are usually expressed statistically, although systems of rules are also common. Pedotransfer functions are developed and applied routinely in land resource assessment and the very number of published functions can cause confusion. The functions have great utility when applied judiciously, but too often they are applied uncritically and, worse still, the existence of a function is sometimes used as an excuse to avoid recording new data. Pachepsky and Rawls (2004) comprehensively treat the topic.

This chapter describes how to choose between functions, formulate new ones and apply them to good effect when assessing land resources. Here two broad classes of pedotransfer functions are distinguished:

- Class 1: Functions that predict soil properties on the basis of other soil properties
- Class 2: Functions that provide spatial predictions of soil properties on the basis of environmental variables. These are considered separately (see *Digital soil mapping*).

Pedotransfer functions in Australia

In the earliest stage, various rules of thumb were formulated to estimate soil properties. For example, Stirk (1957), in North Queensland, suggested an estimate of permanent wilting point (*PWP*) for soil with clay content up to 60% as:

$$PWP = 0.4 \text{ clay.} \quad (\text{Eqn 22.1})$$

This may be regarded as the simplest kind of pedotransfer function.

Williams et al. (1983) were the first to attempt to develop comprehensive functions for Australian conditions. They classified water retention curves using textural class, and provided average parameter values for a power-function model of the curves based on texture class. Williams et al. (1992) later estimated the parameters of Campbell's (1974) model for the water retention curve from texture and structure. Other functions have been developed for estimating

the parameters of this model (e.g. Cresswell and Paydar 1996; Paydar and Cresswell 1996; Smettem et al. 1999). Minasny and McBratney (2002) devised neural networks for estimating parameters of the van Genuchten model for water retention. McKenzie and Jacquier (1997) utilised field morphology to predict saturated hydraulic conductivity.

Most pedotransfer functions have been developed to predict the hydraulic properties of the soil, but there are others (Table 22.1). This situation will change, particularly for chemical properties, because of the seminal research by Janik et al. (1995) and Janik and Skjemstad (1995) that demonstrated how mid-infrared spectroscopy can reliably predict many soil properties at little cost (see *Imaging spectroscopy*).

McKenzie et al. (2000) compiled tables estimating typical ranges for soil properties associated with each principal profile form (PPF) of Northcote (1979). These largely untested pedotransfer functions have been used widely (e.g. Carlile et al. 2001; Bui et al. 2002). Table 22.1 lists some pedotransfer functions developed during the last 25 years for Australian soil. Many other functions exist, but they remain unpublished and are often tabulated as rules of thumb for use within survey agencies (see McKenzie et al. 2002). Efforts are underway to improve access to robust pedotransfer functions (see *Soil inference systems* and References).

Principles

Apply the following principles to choose either an existing function or to develop a new one.

Principle 1 – efficiency

Pedotransfer functions are used mainly to predict properties that are difficult or expensive to measure; they are not intended to predict something that is easier to measure than the predictor. The cost and effort to obtain information on the predictor should be *much less* than for the predictand. Implicit in this principle is that the utility of predictions be greater than that of the predictor.

This principle extends to the use of existing data to predict values of properties that were not measured. A typical example is bulk density. Bulk density is used to convert quantities per unit mass into values per unit volume and *vice versa*. It is crucial in the prediction of water retention yet it has been seldom measured in land resource survey (but see recommendations in *Chapter 17*). Although it is more expensive to determine clay and organic matter content, a model predicting bulk density from clay and organic matter is still considered to be an efficient pedotransfer function. This is because it uses existing soil data (a cost already incurred) to predict a missing variable.

However, predicting the saturated hydraulic conductivity, K_s , of a soil from its structural features, as measured by image analysis, is inefficient. Although there might be a good relationship between the image analysis parameters and K_s , it takes more effort to use current techniques of image analysis. However, prediction from field morphology, if possible, is efficient (e.g. McKenzie and Jacquier 1997).

Principle 2 – uncertainty

Do not use pedotransfer functions unless the uncertainty of predictions can be evaluated and, for a given problem, if a set of possible pedotransfer functions is available, the one with minimum variance is used. Many different pedotransfer functions have been developed to predict the same or similar soil properties. For example, in Australia at least 10 functions are available for predicting water retention, while worldwide there are more than 100. Choose the function that has the smallest error variance or the closest fit between soils used for development

Table 22.1 Examples of pedotransfer functions developed for Australian conditions

Response variable	Predictors	Type and location of soil used	References
Parameters of Campbell equation	Combinations of: field texture class, structure, particle size distribution, organic matter content, bulk density	Southern and eastern Australian wheatbelt	Williams et al. (1992)
Parameters of van Genuchten water retention curve	Particle size distribution, clay content	Sandy soils, Western Australia	Smettem and Gregory (1996)
Parameters of Campbell equation	Two values of θ (h), bulk density	Wheat-belt of Southern New South Wales and Northern Victoria	Cresswell and Paydar (1996)
Parameters of Campbell equation	One value of θ (h), sand, silt, clay, bulk density	Wheatbelt of Southern New South Wales and Northern Victoria	Paydar and Cresswell (1996)
Parameters of Campbell equation	One value of θ (h), clay, bulk density	Near-surface horizons of soils used for cropping in New South Wales, Victoria, South Australia and Queensland	Smettem et al. (1999)
Saturated hydraulic conductivity (K_s)	Clay content	Near-surface horizons of soils used for cropping in Queensland and South Australia	Smettem and Bristow (1999)
Drained upper limit, crop lower limit	Clay content, sand content, coarse fraction, bulk density	Dryland wheat growing areas of Queensland	Littleboy (1998)
Saturated hydraulic conductivity (K_s)	Field morphology	Southern and eastern Australia	McKenzie and Jacquier (1997)
Drained upper limit, crop lower limit parameters of Campbell equation, K_s	Particle size distribution	North Queensland	Bristow et al. (1999)
Water content (θ) at -10 , -33 and -1500 kPa	Particle size distribution, bulk density	General	Minasny et al. (1999)
K_s	Particle size distribution, bulk density	General	Minasny and McBratney (2001)
Parameters of van Genuchten equation	Particle size distribution, bulk density	General	Minasny and McBratney (2001)
Soil erodibility factor	Particle size analysis, organic matter content	Soils from New South Wales and Queensland	Loch et al. (1998)
Phosphorous sorption	pH in NaF	Near-surface horizons from southern regions in Western Australia	Gilkes and Hughes (1994)
pH buffering capacity	Organic matter content, clay content	General	Helyar et al. (1990)
pH buffering capacity	Silt and clay content, organic carbon content	Semi-arid tropics in the Northern Territory and Queensland.	Noble et al. (1997)

and the intended application. Other approaches include applying Bayesian analysis to identify the most probable estimate, or combining all competing estimates with weights that are inversely proportional to their uncertainty.

The uncertainty of a pedotransfer function has two main components.

1. Uncertainty associated with the model: this can be estimated from the non-parametric bootstrap method, or first-order analysis if the pedotransfer functions are generated by the least-squares method.
2. Uncertainty associated with the input data: this can be estimated using Monte Carlo simulation (see *Chapter 24*).

Make sure your input data for a pedotransfer function are within the multivariate space of the original data used for model formulation. Remember, the attribute values for a soil may be within the range of each individual predictor, but the particular combination of values might not have occurred in the original training set.

Types of pedotransfer functions

Variables

Wösten et al. (1995) distinguished between class and continuous pedotransfer functions. The former predict soil properties according to the class to which the soil belongs, and the latter predict soil properties as continuous functions of measured variables.

A further distinction is between the type of predictor and the response variables. These variables can be nominal (either hard or fuzzy), continuous or a mixture. There are thus 16 possibilities, but in accordance with the principles above, not all the combinations qualify as pedotransfer functions. A set of rules by which continuous variables (e.g. sand and clay content) are converted to a class or category (e.g. texture class) is not a pedotransfer function – it is merely a classification.

Functions with continuous predictor variables and continuous response variables are most common. Other examples are as follows.

- Look-up tables that predict continuous soil properties using nominal classes (e.g. Hall et al. 1977; Thomasson and Carter 1992).
- Classification trees that predict hydraulic conductivity from morphological classes (texture, structural grade, areal porosity) (McKenzie and Jacquier 1997). The predictor uses hard classes, and the response is continuous. The classification tree is, in effect, a look-up table with several levels.
- Pachepsky and Rawls (1999) predict water content at potentials of –33 and –1500 kPa with predictors including texture class and taxonomic distinctions such as the soil moisture and temperature regimes. Here the predictor is mixed (hard-class and continuous) and the response is continuous.
- Minasny et al. (1999) predict the van Genuchten parameters using soil properties and fuzzy texture classes. Here the predictor is mixed (fuzzy-class and continuous) and the response is continuous.

Empirical versus more mechanistic functions

Pedotransfer functions can be purely empirical or physico-empirical. Empirical approaches attempt to find relationships between the predictor and response variables using regression analysis or various mathematical models. Most methods for statistical modelling in *Chapter 21*

can be used. Heed the warnings on regression and functional relations described by Webster (1997).

In a physico-empirical approach, the selection of predictor variables and the functional form of the model are based on physical principles. For example, Arya and Paris (1981) translated the particle size distribution into a water retention curve by converting solid mass fractions to water content, and pore-size distribution into hydraulic potential using the capillary equation. Zeiliger et al. (2000) proposed an additive model for soil water retention that assumed that water retention can be approximated by the sum of the components of water retention of its textural composition.

Pedotransfer functions can also be classified according to the role of the response variable. *Single-point* pedotransfer functions predict a soil property, whereas *parametric* pedotransfer functions estimate parameters of a model (e.g. a model describing the water retention curve).

Parametric pedotransfer functions for the water retention curve are most common. Nevertheless, other relationships have been studied; for example, phosphorous sorption characteristics (Scheinost and Schwertmann 1995), potassium characteristics (Scheinost et al. 1997a), the soil strength characteristic (Canarache 1990; da Silva and Kay 1997) and the soil shrinkage curve (Crescimanno and Provenzano 1999). A parametric approach is usually preferred as it yields a continuous function of the relationship, but the physical basis for the relationships between predictor variables and the parameters can be difficult to determine. Many authors have reported difficulties when trying to correlate these parameters to the basic soil properties (Tietje and Tapkenhinrichs 1993). Refer to Scheinost et al. (1997b) and Minasny and McBratney (2002) for more details.

Predictors

Predictors in pedotransfer functions can come from laboratory analysis, field morphology and reflectance spectrometers (see Chapter 17 for an overview). Predictors for environmental correlation (i.e. spatial pedotransfer functions) are also considered (see *Formulation and quality assurance*).

Laboratory data

Laboratory analysis in conventional survey has focused on characterisation of soil profile classes defined by soil morphology. Demand for predictions of soil function has motivated many investigators to analyse large soil databases. Clearly, such investigations are restricted to variables measured in past surveys. The paucity of data on bulk density in Australia illustrates one limitation of these databases. A better strategy is required for formulating new pedotransfer functions. Make sure surveys record the data you need, both for the immediate needs of the survey and for the longer term formulation of new functions (see *Chapter 17* Tables 17.9–17.10 to provide the starting point).

Soil morphology

Most effort has been directed towards correlating laboratory-determined soil properties with those that are more difficult to measure. This has been guided by the availability of comprehensive soil survey databases and the presumption that these properties are most appropriate for predictions. Less attention has been given to soil morphology as a predictor despite its apparent potential (e.g. O'Neal 1949, 1952; McKeague et al. 1984; McKenzie and Jacquier 1997; Lin et al. 1999; Griffiths et al. 1999; Calhoun et al. 2001; Rawls and Pachepsky 2002). One difficulty with conventional systems for describing and interpreting morphology is that the records are almost entirely qualitative. More functional descriptions of soil

morphology are required where the field criteria have a logical physical connection with the properties of interest (McKenzie and Jacquier 1997; Griffiths et al. 1999; Lin et al. 1999). The subsequent relations should be superior to those relying on classified entities such as horizons or soil series.

Imaging spectroscopy

Imaging spectroscopy (see *Chapter 17*), particularly in the near infrared and mid-infrared range, has created new opportunities for measurement in soil survey. The methods provide another form of pedotransfer function where the predictor variables are derived from reflected electromagnetic radiation. Results are encouraging for several physical and chemical properties (see *Chapter 17*).

The spectra recorded by imaging spectroscopy usually contain hundreds or thousands of reflectance values as a function of wavelength. Therefore, methods that reduce the dimensions of the predictors are required. Principal component regression and partial least squares (PLS) methods are commonly used. Principal component regression reduces the dimension of the predictors via principal component analysis, after which linear regression is used between the principal components and soil attributes (Martens and Naes 1989; Chang et al. 2001). Partial least squares (Martens and Naes 1989) extracts successive linear combinations of the predictors while optimising variation in the response and predictor variables.

Several other sensors provide new data for pedotransfer functions (e.g. those for electromagnetic induction, resistivity and gamma-radiometric spectroscopy, see *Chapter 17*). With proper calibration, improved pedotransfer functions will provide better estimates of many soil properties. The combination of field observation, proximal sensing and pedotransfer functions is promising and it may improve the utility of soil survey considerably.

Soil databases

No published sets of soil data are truly comprehensive (but see Prebble 1970; Colwell 1977; Forrest et al. 1985; McGarry et al. 1989; Geeves et al. 1995). The Australian Soil Resources Information System (ASRIS 2007) has been set up to be the main source of data for new pedotransfer functions in Australia. The main limitation is the great variety of analytical methods used for most soil variables (especially cation exchange). The potential of pedotransfer functions cannot be fully realised when source and test data are of mixed quality.

Formulation and quality assurance

Formulate pedotransfer functions according to the guidelines on data analysis (see *Chapter 21*). Consult a professional statistician if there is any doubt about the best approach. Follow the principle of parsimony (Lark 2001) and choose the simplest model that can adequately account for the variation in prediction. Test pedotransfer functions with independent data and avoid overfitting. Wösten et al. (2001) compared three functions for predicting water content at -33 kPa from basic soil properties using the same data set. The accuracy of all was similar and the authors concluded that better results required better data. This is most likely to be a general statement because many soil measurements are inaccurate and imprecise.

Figure 22.1 summarises the main steps in formulating a pedotransfer function. Consider the quality of published pedotransfer functions, and develop new functions only if existing

ones are clearly unsatisfactory. Provide concise statements about the following points when describing new pedotransfer functions.

- Specify the sampled population used for developing the pedotransfer function – for example, morphological, chemical, physical and taxonomic ranges of the soils used, along with the environmental character of the study region including climate, vegetation, parent material and geomorphic setting. Provide relevant statistics (e.g. mean, standard deviation, skewness, median, minimum and maximum, and correlations among variables).
- Specify the target population or scope of inference – ideally the target population and the sampled population will coincide (see *Target and sampled population*). In practice they may differ and in such cases, additional and well-supported assumptions are required to ensure the validity of the pedotransfer functions. For example, a pedotransfer function developed for a given taxonomic class (e.g. Black Vertosols) in one district may be applied to soils belonging to the same class in another district.
- Explain the physical significance of predictor variables used in the pedotransfer function.
- Justify the form of the predictive model (e.g. non-linear versus linear).
- Calculate the uncertainty of the model using the standard first-order Taylor analysis (Chen et al. 1997; Heuvelink 1998, see *Chapter 24*) or the bootstrap method (Efron and Tibshirani 1993).
- If the pedotransfer function is formulated by the least-squares method, list the standard error of the parameters along with their variance–covariance matrix.

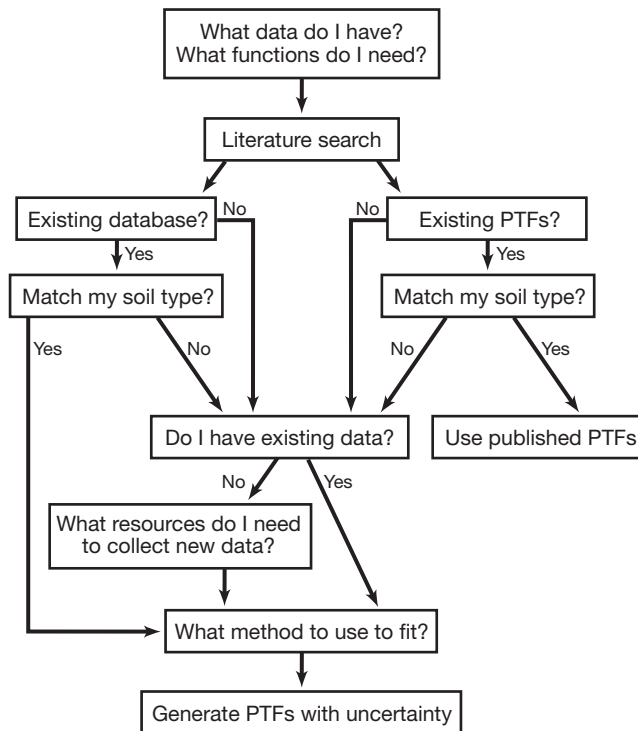


Figure 22.1 A scheme for formulating pedotransfer functions.

Choosing an existing function

Developing new pedotransfer functions is arduous and generally requires a large soil database of good quality. Utilise existing functions where possible, but do not extrapolate beyond the range of the original training set. Many Australian soils are formed of, or in, strongly weathered materials. Many have clay-rich horizons, can shrink and swell, contain little organic matter or are sodic or saline (or both). As a consequence, pedotransfer functions from different environments (e.g. those from Europe or North America) are unlikely to be suitable. Therefore, it is necessary to establish the domain from which a pedotransfer function has been derived – it may be defined by soil horizons (Hall et al. 1977), soil classes (Batjes 1996), textural classes (Tietje and Hennings 1996), hydraulic-functional horizons (Wösten et al. 1986), temperature regimes, moisture regimes (Pachepsky and Rawls 1999), numerical soil classification (Williams et al. 1983) or management units (Droogers and Bouma 1997) to mention just a few possibilities.

Calibration may be required to translate available data to the required scales of the predictor variables. The International and Australian systems for particle size analysis, for example, define the grain size of sand to be 20 μm to 2000 μm , while the FAO/USDA criteria use diameters of 50 μm to 2000 μm . Minasny and McBratney (2001b) provide equations for converting between systems. Little (1992) and Henderson and Bui (2003) provide calibrations between pH measured in water and calcium chloride (CaCl_2) solution.

Wherever possible, test published pedotransfer functions using available data. Many pedotransfer functions have limited applicability. They may be accurate for the original training data but unreliable in other contexts (Wösten et al. 2001). Tietje and Tapkenhinrichs (1993) and Minasny and McBratney (2000) provide guidance on the selection of functions.

Use consistent methods when applying pedotransfer functions to soil profiles, or across fields and larger areas. For example, consider the case where data on particle size are available for each layer in a soil profile but bulk density for only a few. Although there are pedotransfer functions that use particle size analysis alone and particle size plus bulk density as inputs, use the function that takes particle size plus bulk density as inputs for each layer. For layers without measurements of bulk density, predict their values by interpolating between layers or use a prediction from particle size data. Using different pedotransfer functions across a field, or within layers in a profile, can produce different values due to differences in the structure of the functions.

Digital soil mapping

Most methods of survey use relationships between soil properties and more readily observed environmental variables as a basis for mapping (e.g. see *Chapter 19*). In recent years, an explicit analogue of conventional survey practice has been developed – it will be referred to here as *environmental correlation* (Austin and McKenzie 1988). Various studies have reported predictive relationships between quantitative environmental variables and soil properties (e.g. McKenzie and Austin 1993; Gessler et al. 1995; Odeh et al. 1995; Cook et al. 1996; McKenzie and Ryan 1999; Johnston et al. 2003; McBratney et al. 2003; Pachepsky and Rawls 2004; McKenzie and Gallant 2006).

Some of the most promising environmental variables are those generated by digital terrain analysis (see *Chapter 6*) and gamma radiometric spectroscopy (see *Chapter 13*). Digital terrain analysis allows us to generate variables that reflect geomorphic, climatic and hydrological processes. Gamma radiometric remote sensing captures differences in parent material, most notably particle size and mineralogy near the surface. In the future, temporal analysis of remote sensing (see *Chapter 12*) should provide another valuable source of environmental data for predicting soil properties.

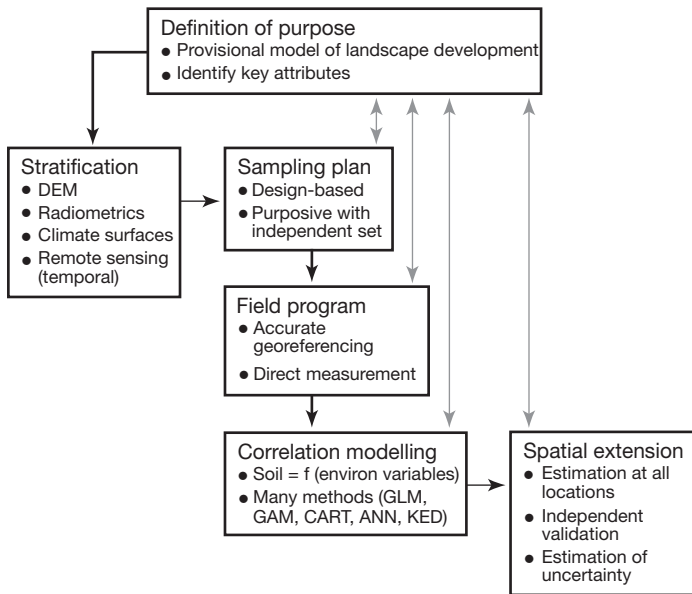


Figure 22.2 Steps and options involved in digital soil mapping using environmental correlation.

The logic of environmental correlation is presented in Figure 22.2. There are various options surrounding each step of the method, and in practice environmental correlation can be done geostatistically (e.g. as co-kriging and kriging with external drift) or, at the other extreme, as a rule-based procedure resembling conventional survey. The defining features of environmental correlation are:

- explicit modelling of relations between soil properties measured at field sites and environmental variables by digital techniques
- use of environmental variables to predict site observations across the complete region
- a capacity to update the model and spatial predictions as new information becomes available.

The computational sophistication of the approach can vary greatly. Sampling during model building can be purposive or statistically based, and there is the option for constructing sophisticated models of spatial dependence if a geostatistical approach is adopted (see Chapter 23).

Environmental correlation has become feasible for land resource survey for the following reasons.

- High-quality environmental data relevant to soil distribution are now available across many parts of Australia.
- Geographical information systems (GISs) and statistical software facilitate analysis.
- Global positioning systems (GPS) allow field data to be accurately registered with remotely sensed data.

A significant limitation for environmental correlation as a method is the requirement for predictors to be readily observable and suited for spatial prediction. Complex landscapes may have few suitable predictors as a result of subtle terrain features, no reliable vegetation indicators, substantial short-range variation (i.e. at a finer grain than the environmental predictor), or a dominance of subsurface structures controlling soil distribution. The principles of efficiency and uncertainty apply (see *Principles*). For example, the environmental predictors must

be cheaper to measure than the soil variables of interest, otherwise it is more sensible to record the soil directly and interpolate.

Definition of purpose and provisional models

As with conventional survey, environmental correlation involves the iterative development of region-wide predictive models. The complexity and range of spatial and temporal scales over which soil-forming processes operate (and have operated) make it almost impossible to develop models for spatial prediction that are quantitative, mechanistic and mathematical, although there have been some notable attempts and interesting developments (e.g. Dietrich et al. 1995; Minasny and McBratney 2001a). Pedotransfer functions for digital soil mapping will, as a result, be local in application and have varying levels of empiricism. It is unlikely that functions developed for one region can be applied to map others (see *Predictors*).

The initial phase includes activities that are listed sequentially but which develop in parallel (or iteratively) as the model is refined – hence the feedback loops in Figure 22.2. To begin, formulate a provisional soil-landscape model using existing knowledge and available data (e.g. existing sample sites, mapping from adjacent areas); the considerations are similar to those concerning conventional survey (see *Chapters 2 and 18*).

Make a preliminary analysis using environmental data and identify potential predictor variables. Here, the quality of the environmental data will have a large impact on the success or otherwise of the environmental correlation. In most parts of Australia, prerequisites include a digital elevation model with fine resolution (preferably better than 25 m) and airborne gamma radiometric spectroscopy (flown at a line spacing of about 200 m or less). In some environments, these requirements can be relaxed if good quality remotely sensed data are available (e.g. temporal or hyperspectral data – see *Chapters 11 and 12*).

Choose environmental variables that predict primary soil attributes rather than soil types. This overcomes the joint assumptions that soil properties are highly correlated and that general-purpose soil types can be defined and mapped. The immediate goal is to measure and describe the continuum of soil properties and classify later if required (see *Chapter 2*). This demands considerably more measurement than in qualitative survey. There is the additional consequence that for each predicted attribute, one model of soil and landscape variation is needed (in contrast to the unitary model that is produced in most qualitative survey). Where there is strong covariance between soil attributes, the predictive models for each attribute will be similar.

As with all surveys, the targeted soil properties must be specified in the Terms of Reference – the measurement strategy will nearly always require procedures for developing new, or applying existing, pedotransfer functions for the relevant soil properties. The data requirements of simulation models should be also carefully considered (see *Chapter 28*).

Stratification and sampling

Stratification is essential in most surveys. It provides the framework for sampling, measurement and prediction. Existing maps from conventional survey (or other qualitative maps) can be used for stratification but it must be possible to calculate the inclusion probability for any point if statistical sampling is planned. The area of each stratum needs to be known as well as the number of potential sample points in each. It is best for the stratification to discriminate zones exhibiting different landscape processes. This should result in better prediction. Stratification can also be achieved through classifications of environmental variables. Ryan et al. (2000) and McBratney et al. (2003) list environmental variables that have proven useful for stratification and prediction (Table 22.2). Refer also to the chapters on geology, terrain analysis, hydrology and remote sensing (see *Chapters 4, 6, 7 and 11 to 13*).

There are many options for sampling. McKenzie and Ryan (1999) provide an example where geology, terrain, and climate variables were used for stratification. They also reserved a percentage of sites for purposive sampling so that anomalies and areas of stratigraphic significance could be examined. An alternative approach is to use Latin hypercube sampling (see *Chapter 24*). Key-area sampling can be used to good effect during the initial phases of a study (see *Chapter 18*).

In practice every available line of evidence should be used to build predictive models (e.g. qualitative knowledge from other landscapes and data collected using purposive sampling) and then model performance can be assessed through an independent validation phase that is strictly statistical. The advantages of a fully statistical approach to survey include unbiased prediction and estimation of uncertainty. However, this assumes the predictor variables (e.g. terrain variables, gamma radiometric spectroscopy) are measured without error – since this is rare, the resulting predictions carry an unknown level of bias and uncertainty. Overcoming this problem is a matter of determining bias and uncertainty from an independent validation sample (see *Chapter 18*).

Correlation modelling

Environmental correlation is so named because it exploits useful *correlations* with environmental predictor variables. That said, always check predictive models to make sure they have a rational physical basis.

The procedures for developing models of soil distribution in landscapes were outlined (see *Chapters 5 and 18*). The conceptual basis behind them is similar in environmental correlation—the contrast is in the explicit nature of these relationships and the tools used to derive, formulate and present these relationships. At its simplest, the pedotransfer function can be expressed as a set of rules formulated during conventional field work. Corner et al. (2002) provide a good example of a more formalised approach using rule-based systems for environmental correlation. Another less formal example is McKenzie and Gallant (2006).

The most useful statistical methods for environmental correlation (see *Chapter 21*) are:

- generalised linear models (including classical regression, analysis of variance, and logistic regression)
- tree-based methods (classification and regression trees)
- generalised additive models
- Bayesian methods.

Exploratory and confirmatory methods only occasionally reveal relations that have not already been detected or suspected during field survey. Their main role is often to dispel pet theories on patterns of soil–landscape variation – this can be a sobering experience. A good rule-of-thumb is to be highly suspicious of correlations between environmental variables and soil properties that cannot be explained by pedological principles and physical processes. This may seem obvious, but it is very easy when analysing large data sets to overlook results that are spurious or an artefact of the statistical method. Be particularly careful with tree-based methods and neural networks because over-fitting of parameters can easily occur (see *Chapter 21*).

If the survey area is small, then one relation for each predicted attribute might be sufficient. For larger areas, there are likely to be subregions, each with different relations for predicting attributes. The end result is often a large and complicated set of relations.

Some common issues of analysis include the following.

- Consistent departures from predictions in particular parts of a region. This suggests a missing predictor variable ('lurking variable'). Augment the original sampling, check the stratification and reformulate the models for the relevant areas.

- ▶ Consistent departures from predictions for a minority of attributes but satisfactory prediction for the remainder. This arises when the sampling intensity required to develop useful predictive models varies among attributes and some attributes require more intense sampling (e.g. due to greater short-range variation).
- ▶ Reasonably accurate but imprecise predictions. This is a common result and it can be caused by too little sampling, large short-range variation in the target variables, imprecise environmental predictors and multiple sources of error (e.g. when the target variable is estimated using a pedotransfer function).

The precision and accuracy needs to be matched to the resources available. A lack of resources may result in inadequate prediction of one or more attributes. In your reports, ensure clients and survey users understand these limitations.

Independent validation

The following recommendations on independent validation are similar to those for conventional survey (see *Chapter 18*). Validation requires a statistically based phase of sampling, and again the most effective approach will depend on the context of the individual survey; advice from a qualified statistician should be sought. The requirements for validation are as follows.

- ▶ Identify a set of variables you want to predict and which at the same time can be measured cheaply.
- ▶ Sample either the complete region or particular areas by stratified random, multistage stratified random, or cluster sampling. In most instances, a sample size of between 50 and 200 sites should be sufficient although the actual figure will depend on the scope of the study.
- ▶ Prior to fieldwork, prepare an explicit protocol for site location in the field that includes criteria for rejecting unsuitable sites (e.g. river channels, sealed roads, capped land).
- ▶ Undertake field measurement and, where possible, use different staff to those responsible for the original survey.
- ▶ Compare the estimates for the target variables derived from environmental correlation with those derived from the new sample.
- ▶ Compute measures of predictive success (e.g. standard errors of prediction, contingency tables, graphs of predicted versus observed variables).
- ▶ Report the reliability of prediction in a form that can be understood by the user. In particular, use the results of the validation sampling to make statements on uncertainty (see *Chapter 24*).

As with conventional survey, it will take several years before a body of evidence is accumulated to determine what predictive success is possible across a broad range of landscapes in Australia.

Models used in environmental correlation often embody variables that capture variation at the local, hill-slope and more regional scales. This is in accord with field experience – the factors controlling soil distribution are always multiscaled. The significant advance provided by high-resolution digital elevation models and gamma radiometric remote sensing is that they predict soil variation at a fine grain across extensive areas. By contrast, conventional soil surveys cannot readily portray soil variation at length scales of 50 m to 500 m (because of cartographic limitations and constraints caused by the reliance on soil types). Environmental correlation can do better because a good proportion of this short-range variation can be represented. In this way, it is possible to account for more than 30% to 50% of the variation in soil properties across a landscape as achieved by qualitative surveys (see *Chapter 21*).

Survey products

A major difference environmental correlation and conventional survey is that a greater variety of primary and derived outputs is possible. At a secondary level, decisions are also needed on the storage and reporting of data.

Primary outputs

Key outputs from environmental correlation are the sets of digital raster surfaces for each predicted attribute. These will have associated metadata that:

- describe the cartographic, geodetic and geographical nature of the surfaces
- point to the descriptions of reliability, uncertainty and usage constraints
- describe the models and environmental data used to produce the surfaces.

These descriptions are needed to update the rasters as data improves or the model refined. Associated with each attribute surface will be another surface measuring uncertainty (there may be several forms of uncertainty measures).

Other primary outputs include:

- the environmental data sets used for modelling
- soil profile data
- the validation data set
- predictive models.

Metadata are needed for each output. Store all outputs digitally and attach clear annotation.

Secondary outputs

Secondary outputs will be often in the form of raster surfaces, but polygonal surfaces may be included depending on demand. Rasters of soil attributes will normally provide the inputs to static or dynamic land evaluations. It is also worthwhile producing maps of soil profile classes. These are valuable for communicating broad concepts and maintaining consistency with qualitative surveys. Soil types can be generated by numerical taxonomy (see *Chapter 21*) or through the application of a simple digital key developed for the particular study. These maps can be augmented with summary statistics for the particular soil attributes – boxplots are particularly effective (e.g. see *Chapter 21*, Figure 21.1).

Combining pedotransfer functions of Classes 1 and 2

Two pathways exist for applying pedotransfer functions in digital soil mapping (i.e. pedotransfer functions of Classes 1 and 2). These are illustrated in Figure 22.3 where the digital soil information provides input to a transfer function (e.g. available water capacity) and the results are required at a larger support than the original measurements. For example, data on texture and bulk density (point support) may be used as input to a transfer function for available water capacity, and the results are needed at the larger support of a small catchment. The options are as follows.

- The pedotransfer function is applied at each field site with predictor variables recorded during the survey. The results are then extended spatially by interpolation (e.g. by kriging or environmental correlation).
- The predictor variables are first extended spatially and the estimates are used in the pedotransfer function at all locations (e.g. pixels).

It is best to run the model at the point support for which it was developed and then aggregate the model output (Heuvelink and Pebesma 1999).

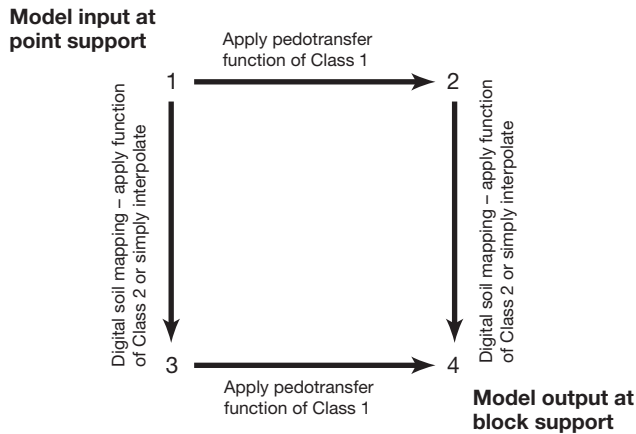


Figure 22.3 Two pathways from input at point support to output at block support (after Heuvelink and Pebesma 1999).

Merits

Digital soil mapping by environmental correlation is fairly new and it has several positive features.

- 1 The method combines familiar concepts of qualitative survey with new techniques and quantitative methods.
- 2 Methods are explicit and repeatable.
- 3 The method produces predictions of individual soil properties that can be used for a wide range of purposes.
- 4 The results can be readily updated when and where required.

Soil inference systems

A great deal of effort has been devoted to the formulation of new pedotransfer functions, but much less has been directed to using available pedotransfer functions. In response, McBratney et al. (2002) proposed the concept of the *soil inference system* (SINFERS), where pedotransfer functions become the knowledge rules for soil inference engines. A soil inference system takes measurements of known dimensions with a given degree of uncertainty, and infers, by means of properly and logically conjoined pedotransfer functions, values that we do not know (and with maximal accuracy).

Dale et al. (1989) discussed the role of expert systems in soil classification, and similar principles can be applied to the proposed inference system. This is illustrated in Figure 22.4, where the system has a source, an organiser and a predictor. The sources of knowledge to predict soil properties are collections of pedotransfer functions and soil databases. The organiser arranges and categorises the pedotransfer functions with respect to their required inputs and the soil types from which they were generated. The inference engine is a collection of logical rules that select the pedotransfer functions with the minimum variance. The rules can simply be a collection of ‘if ... then’ statements, or based on probabilistic Bayesian inference. Uncertainty of the prediction can be assessed by Monte Carlo simulations. The inference system operates through a user interface that will return the predictions of soil physical and chemical properties with their uncertainties based on the information provided.

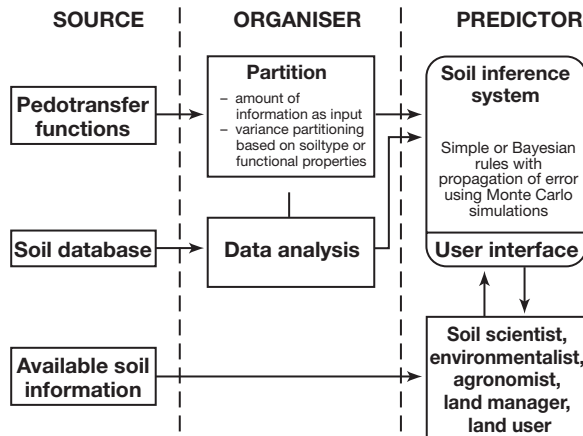


Figure 22.4 A soil inference system.

McBratney et al. (2002) demonstrated the first approach towards building a soil inference system by creating a rudimentary spreadsheet. It had two new features worth noting. First, it contains a suite of published pedotransfer functions – the output of one pedotransfer function can act as the input to other functions (if no measured data are available). Second, the uncertainties in estimates are used as inputs and the uncertainties of subsequent predictions are calculated. The input consists of the essential soil properties and the inference engine. The system performs two functions.

1. It predicts all the soil properties using all possible combinations of inputs and pedotransfer functions.
2. It then selects the combination that leads to a prediction with the minimum variance.

A more complete system for soil inference is being developed, and if successful, it will be incorporated into the Australian Soil Resource Information System (ASRIS 2007).

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Geostatistics

R Webster

Introduction

Geostatistics began as a body of statistical techniques for estimating the amounts of metals in ore-bearing rocks. Late in the 1970s, pedologists realised that the same technology could be adapted to soil survey; they realised that they could make maps of individual soil properties without first having to classify the soil and getting embroiled in all the doubts and controversy that that entailed. The maps are derived by ‘contouring’ from dense grids of values estimated from more or less sparse sample data. The procedure for estimation is known as ‘kriging’, after DG Krige who developed it empirically in the South African gold fields (see Krige 1966). Kriged estimates are unbiased and of minimum variance, and in this sense they are optimal. Theory and practice over the last 25 years has provided earth scientists with a sound technology that can be readily applied for estimating and mapping land resources.

This chapter describes briefly the underlying theory and assumptions of geostatistics. It then tackles the practical steps a surveyor must take to apply the technology. Geostatistics is best suited to intensive studies of small regions where spatially dense sampling is feasible, with sites being located within the range of spatial dependence for each attribute. Larger regions will inevitably include landscapes with diverse histories and the contrasting patterns of soil variation will demand the determination of several sample variograms.

Theory

The practice of geostatistics is based on the theory of random functions, or stochastic processes. In this theory a variable at any point $\mathbf{x}$ on the land surface possesses not a single value but many values. Most environmental variables, such as the phosphorus content of soil or the salinity of groundwater, are continuous and so the distribution at $\mathbf{x}$ has an infinite number of values. In the real world, there is only one value at $\mathbf{x}$, and the theory treats this value, the value observed there, as just one drawn at random from some probability distribution according to some law.

Some technical terms and notation

A consistent notation is needed to pursue the theory and for the equations later in the chapter. The location of a place on the Earth’s surface is denoted by the vector $\mathbf{x}$, comprising two Cartesian coordinates, x_1 for (say) eastings, and x_2 for northings. Thus, $\mathbf{x} \equiv \{x_1, x_2\}$. The random variable at $\mathbf{x}$ is denoted $Z(\mathbf{x})$ (notice the capital), and its realisation is denoted $z(\mathbf{x})$ (now with a lower case z). The lower case form $z(\mathbf{x})$ is also used for an observation.

On the land surface there are infinitely many points, and each point $\mathbf{x}_i$, $i = 1, 2, \dots, \infty$, has its own $Z(\mathbf{x}_i)$. Thus, there is a doubly infinite set of values that constitute an ensemble, and the actuality on the ground is one realisation of the ensemble. The set of random variables $Z(\mathbf{x}_1)$, $Z(\mathbf{x}_2)$, $\dots$, constitutes a *random function*, *random process* or *stochastic process*. The set of actual values that comprise the realisation of $Z(\mathbf{x})$ is known as a *regionalised variable*, and the theory on which geostatistics is built is known as the *theory of regionalised variables*, the name given it by Georges Matheron (1965).

Spatial covariance, correlation and the variogram

As soil forms a continuous mantle on the land surface, and that many of its properties are themselves continuous, means that the random variables from which they are imagined to derive are correlated spatially at some scale, or *autocorrelated*. This autocorrelation is defined from the corresponding autocovariance between any two places $\mathbf{x}$ and $\mathbf{x} + \mathbf{h}$, separated by the vector $\mathbf{h}$ as follows (Equation 23.1):

$$\begin{aligned}\text{cov}[Z(\mathbf{x}), Z(\mathbf{x} + \mathbf{h})] &= E[\{Z(\mathbf{x}) - \mu\}\{Z(\mathbf{x} + \mathbf{h}) - \mu\}] \\ &= E[\{Z(\mathbf{x})\}\{Z(\mathbf{x} + \mathbf{h}) - \mu^2\}] \\ &= C(\mathbf{h}),\end{aligned}\tag{Eqn 23.1}$$

where μ is the mean of the process. The autocovariance at lag zero, $C(\mathbf{0})$, is the variance of the process, σ^2 . Dividing $C(\mathbf{h})$ by this quantity gives the autocorrelation, $\rho(\mathbf{h})$ (Equation 23.2):

$$\rho(\mathbf{h}) = C(\mathbf{h})/C(\mathbf{0}).\tag{Eqn 23.2}$$

The vector $\mathbf{h}$ defines the separation between the pairs of points in both distance and direction. It is termed the *lag*. Both the autocovariance and the autocorrelation depend on the lag and only on the lag, and as functions of the lag they are the autocovariance function and correlogram respectively. Provided the mean is constant they do not depend on absolute positions. Indeed, their very existences demand that the mean and variance are constant, as inspection of Equation 23.1 shows. Processes with these properties are said to be *weakly stationary* or *second-order stationary*.

In many instances in land resource survey, the means of the variables of interest appear to change across a region and the variance to increase without bound as the area increases. In these circumstances there is no constant μ that we can insert in Equation (23.1), and so the covariance cannot be defined. Matheron (1965) recognised the problem this created, and he solved it by defining another quantity to describe the relations between pairs of points. He took the view that whereas, in general, the mean might not be constant, it would at least be constant for short lag distances, so that the expected differences would be zero (Equation 23.3):

$$E[Z(\mathbf{x}) - Z(\mathbf{x} + \mathbf{h})] = 0.\tag{Eqn 23.3}$$

Further, he replaced the covariances by the variances of differences (Equation 23.4):

$$\begin{aligned}\text{var}[Z(\mathbf{x}) - Z(\mathbf{x} + \mathbf{h})] &= E[\{Z(\mathbf{x}) - Z(\mathbf{x} + \mathbf{h})\}^2] \\ &= 2\gamma(\mathbf{h}).\end{aligned}\tag{Eqn 23.4}$$

Equations 23.3 and 23.4 constitute Matheron's *intrinsic hypothesis*. They require weaker assumptions than those of second-order stationary, and being easily satisfied they have a wider field of application. Matheron called the quantity $\gamma(\mathbf{h})$ the 'semivariance' (it is half the variance of the difference). However, it represents the variance per point. Also, like the covariance, it depends only on the separation and not on the position $\mathbf{x}$.

The function $\gamma(\mathbf{h})$ was originally called the ‘semivariogram’, though now it is usually termed simply the *variogram*. It is the function we shall use henceforth in this chapter to describe spatial variation in variables on the land surface.

Kinds of variogram

Three kinds of variogram are distinguished. The first is the theoretical variogram as defined in Equation 23.4 above. This is the variogram of the imaginary random process from which the reality is a realisation. The second is the regional variogram; it is the variogram that we should compute if we had complete information for the region surveyed. In practice our information is fragmentary because only sample observations are available, and it is from these that a sample variogram is computed, often called an ‘experimental’ variogram.

The experimental variogram

You can form the sample variogram, or experimental variogram, from data by the method of moments, as follows. Denote the data by $z(\mathbf{x}_1), z(\mathbf{x}_2), \dots$. Then compute for a given lag $\mathbf{h}$ the semivariance (Equation 23.5):

$$\hat{\gamma}(\mathbf{h}) = \frac{1}{2m(\mathbf{h})} \sum_{j=1}^{m(\mathbf{h})} \{z(\mathbf{x}_j) - z(\mathbf{x}_j + \mathbf{h})\}^2, \quad (\text{Eqn 23.5})$$

in which $m(\mathbf{h})$ is the number of paired comparisons at that lag. Choose a sequence of lags and repeat the calculation for each to form an ordered series of semivariances. The result is the experimental variogram, $\hat{\gamma} = (\mathbf{h}_k)$, $k = 1, 2, \dots$, for those data.

If you sample at regular intervals on a grid or a transect, then you increment $\mathbf{h}$ by the same intervals, bearing in mind that as the direction through the grid changes, so also will the distance between points. If the data are irregularly scattered, then the pairs of points must be placed in ‘bins’, limited in both distance and direction. Figure 23.1 shows the geometry of this.

In many instances variation is much the same in all directions, and in these circumstances the vector $\mathbf{h}$ can be treated as a scalar, h , in distance only, so that $h = |\mathbf{h}|$.

The experimental variogram can then be plotted as a simple graph of $\hat{\gamma}(\mathbf{h})$ against h , as in Figure 23.2.

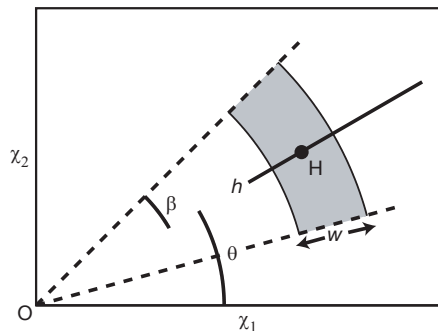


Figure 23.1 Geometry for discretisation of space around each sampling point for the experimental variogram. The nominal lag is h , θ in which h is the nominal distance and θ is the direction. All separations between sampling points falling within the grey region, the ‘bin’, contribute to the semivariance at that nominal lag.

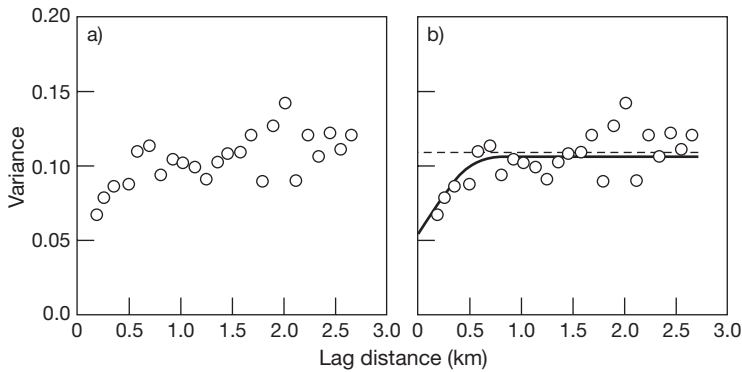


Figure 23.2: Variogram of the $\log_{10}$ of the phosphorus content of the topsoil at Ginninderra: (a) the experimental values only; and (b) with a spherical model fitted. The parameters of the model are $c_0 = 0.0528$, $c = 0.0535$ and $\alpha = 0.73$ km. Data from Webster and Butler (1976).

Outliers, robust estimation and transformations

Estimation of the variogram by the method of moments, Equation 23.5 above, is by far the commonest method. It is sensitive to outliers and strong skewness in data, both of which tend to increase the semivariances over the whole range of lags. If you think the outliers are mistakes, you should remove them (see *Chapter 21*). If you think that, though correct, they are exceptional (and do not properly belong to the target population) then again you are best advised to remove them from your data before computing the variogram. If after due consideration you decide to retain outliers, you can diminish the effect they have on your estimates of $\gamma(\mathbf{h})$ by using robust methods. The same applies to values in the long tails of strongly skewed distributions. Robust estimation of the variogram is a somewhat special topic about which there is no general agreement, and you should seek professional advice before taking this course. You should also read Lark (2000) who describes some of the methods and compares results from them.

For data that are strongly skewed, a better course is to transform the data to stabilise the variances. Many variables with which resource surveyors have to deal are strongly positively skewed, with distributions that approximate to log-normal (i.e. are approximately normal when transformed to logarithms). If your data appear to be distributed in this way, then transform them and compute the variogram on the logarithms. Chapter 21 describes other variance-stabilising transformations. The variogram that you compute applies to the transformed data and that if you use it for kriging, for example, you must krig from the transformed data, and your kriged results will still be in the transformed scale.

Modelling the variogram

The experimental variogram summarises the spatial correlations among the data; it does not describe directly the correlations in the region generally. Furthermore, its values are only *estimates* of the mean semivariances for the chosen lags and are subject to error (arising largely from sampling fluctuation). When plotted, the sample variogram appears more or less erratic, again as in Figure 23.2. The true regional variogram is a continuous function, and you need such a function to generate the semivariances for the kriging equations (see *Kriging: spatial estimation or prediction*). In order to krig you must have a model of the variogram (or covariance function) from which to obtain semivariances. Therefore, the aim of modelling is to fit a function that passes through the experimental points, following the general trend and ignoring

point-to-point fluctuations. In practice, it is best to fit the simplest model that makes sense, subject to certain conditions (mentioned next).

It will not serve to use any mathematical function that appears to follow the trend and to lie close to the experimental points. The function you choose needs to be one that can describe random variation and still guarantee non-negative variances when random variables are combined. In technical jargon, the function must be *conditional negative semidefinite* or CNSD. In some of the literature such functions are called *authorised* functions.

There are two main families of simple CNSD functions commonly used in geostatistics, those that are bounded and those that are unbounded. These are discussed in reverse order with equations for the isotropic case (i.e. variation is independent of direction).

Unbounded models

Power functions

Unbounded variation may seem strange on a finite Earth. Yet it often happens that an experimental variogram appears to increase without limit within the region sampled. The simplest models to describe such variation, γ , are the power functions (Equation 23.6):

$$\gamma(h) = wh^\alpha \text{ for } 0 < \alpha < 2 \quad (\text{Eqn 23.6})$$

where w describes the intensity of the variation and α describes the curvature. If $\alpha = 1$, then the function is a straight line and w is the gradient. If $\alpha > 1$, then the variogram follows an upward concave curve; if $\alpha < 1$ then its curve is convex upwards. The limits 2 and 0 are excluded. A function with $\alpha = 2$ would be parabolic with gradient 0 at the origin and describe continuous non-random variation; hence, it is not allowed. If $\alpha = 0$, then the variogram would be constant for all $h > 0$.

Figure 23.3 shows power functions with various values of α .

Bounded models

Bounded variation is more common than unbounded variation, and the variograms chosen by practitioners have more varied shapes. In most instances the experimental semivariances appear to reach or approach a maximum with increasing lag distance and then remain more or less constant thereafter. This maximum is known as the *sill* of the variogram. If it is reached at

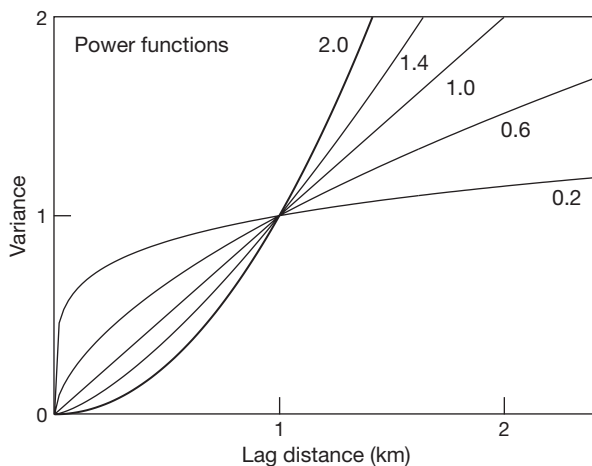


Figure 23.3: Permissible isotropic power functions for variograms with their exponents.

some finite lag distance, then that distance is known as the *range*, or sometimes as the *correlation range*. It is the limit of spatial dependence. It signifies that all the variance in the region is encompassed within that distance from any point.

There are a dozen or so bounded models in use, and only the most popular is described below.

Spherical model

This popular function illustrates the main features of bounded variogram models (Equation 23.7):

$$\begin{aligned}\gamma(h) &= c \left\{ \frac{3h}{2a} - \frac{1}{2} \left(\frac{h}{a} \right)^3 \right\} & \text{for } h \leq a \\ &= c & \text{for } h > a.\end{aligned}\quad (\text{Eqn 23.7})$$

It has two parameters, c , which is the sill variance and, a , the range (Figure 23.4a).

Exponential model

The exponential function has the formula (Equation 23.8):

$$\gamma(h) = c \left\{ 1 - \exp\left(-\frac{h}{r}\right) \right\}, \quad (\text{Eqn 23.8})$$

where c is the sill as before, and r is a distance parameter. The popular function approaches its sill asymptotically and so has no finite range. However, for practical purposes it has an effective range of $a = 3r$, a quantity often quoted in the literature. At this lag distance the function reaches $0.95 \times$ its sill (Figure 23.4b).

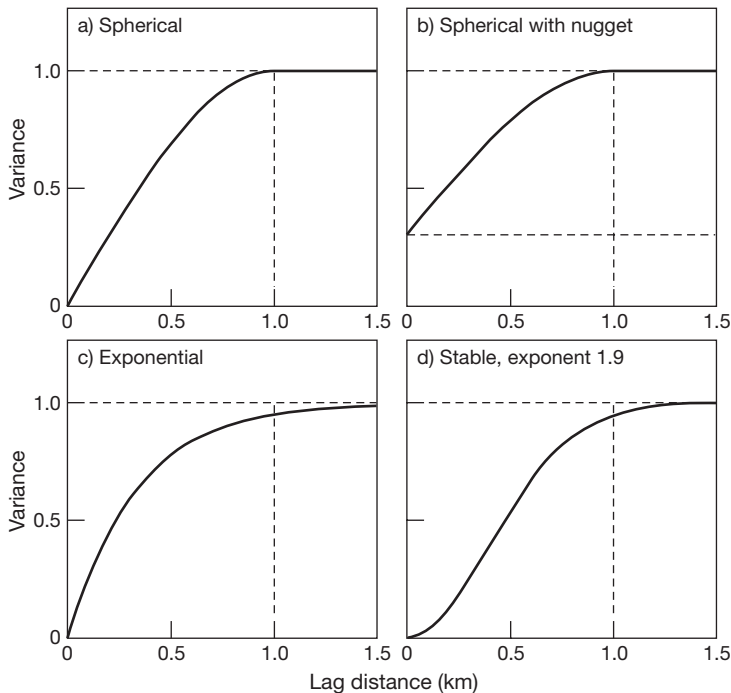


Figure 23.4 Some bounded isotropic models for variograms. Their upper bounds (their sills) are drawn with dashed lines. The vertical dashed lines in the upper two graphs are the ranges, those in the lower graphs are the effective ranges. In (b) the model cuts the ordinate at a value greater than 0, the nugget variance, indicated by the lower dashed horizontal line.

Stable models

Both of the above models increase from their origins with decreasing gradient. Some variograms, in contrast, appear to increase in gradient from the origin and then curve with decreasing gradient. A general equation for this kind of behaviour (Equation 23.9) is:

$$\gamma(h) = c \left\{ 1 - \exp \left(- \frac{h^\alpha}{r^\alpha} \right) \right\}, \quad (\text{Eqn 23.9})$$

in which the parameters c and r have the same meaning as in the exponential model, but in which there is the additional parameter, α , with $1 < \alpha \leq 2$. Clearly, when $\alpha = 1$ the model is the exponential. As α increases beyond 1 the more marked becomes the reverse curvature near the origin. The limiting value of $\alpha = 2$ defines the so-called *Gaussian* model. It defines smooth variation, and though the model is admissible for a variogram, do not use it for kriging because it leads to instability. If the Gaussian model appears to fit your experimental values well, then try setting α to 1.9 or 1.95 to obtain stable results.

You can find more comprehensive lists of permissible variogram functions and their definitions in Chilès and Delfiner (1999) and in Webster and Oliver (2007).

Nugget variance

A particular form of bounded variation gives rise to the ‘pure nugget’ variogram. Any variable that is continuous on the land surface has a semivariance of 0 at $\mathbf{h} = 0$. In practice, however, it is usually found that a smooth curve fitted to the experimental variogram cuts the ordinate at some value larger than zero. This intercept on the ordinate is known as the *nugget variance*. It represents variation over distances much shorter than the smallest sampling interval plus measurement error. If all the variation is encompassed within that interval, then the variogram will appear flat (i.e. pure nugget) (Equation 23.10):

$$\gamma(h) = c_0 \quad (\text{Eqn 23.10})$$

a constant for all h .

Most variogram models contain this additional parameter.

Other forms

The simple models such as the power, spherical and exponential functions with the additional nugget variance may be regarded as combinations of two functions. Other combinations might be desirable to describe nested structures on two or more spatial scales. In principle, any combination of CNSD functions is itself CNSD. So, for example, you might fit a combination of two spherical functions with two distinct ranges, say, a_1 and a_2 , and their associated sill variances, c_1 and c_2 .

In some instances the variogram appears to fluctuate in a systematic manner, suggesting that the underlying function has some degree of periodicity. You might therefore wish to fit a damped cosine function, sometimes known as a ‘hole effect’ model. The ‘hole’ appears as a minimum in the covariance function and as a hump or maximum in the variogram. Again, Chilès and Delfiner (1999) and Webster and Oliver (2007) give details of the allowed functions.

A more common departure from the simple forms described above is one of ever increasing gradient, either overall such that the exponent in the unbounded power function, Equation 23.6, exceeds 2, or over short lag distances such that $\alpha > 2$ in Equation 23.9. The first is almost certainly caused by a regional trend in the variable Z . The data combine components from both the trend and the random fluctuation about the trend. So the experimental variogram contains variation from both, whereas any true variogram can describe only the random component. In the second case the trend is likely to be local only, but it is still too smooth to be random. In both situations the two sources of variation need to be distinguished but modelled

simultaneously. How best to do this is still a topic of research, and if you find a trend in your data, then you should seek professional advice.

Fitting models

Fitting models to experimental variograms is controversial. Some texts advise practitioners to fit models by eye alone. I cannot recommend this. By all means start with a graph of the experimental variogram, and then proceed as follows.

1. Compare the general form of the experimental variogram with those of the common, simple CNSD models for random variation in two dimensions. Choose a few that appear to have the correct form.
2. Fit each model in turn using an authenticated program by minimising a weighted least-squares criterion. Choose weights in proportion to the number of paired comparisons, $m(h)$ in Equation 23.5, and set approximate starting values for the non-linear parameters, α in Equations 23.6 and Equation 23.9, a in Equation 23.7 and r in Equations 23.8 and 23.9. Tabulate the residual sums of squares and residual mean squares as fitting criteria.
3. Select the function for which the criteria are least. Plot the fitted function on the same pair of axes as the experimental variogram and examine the result. If the function appears to fit well, then accept it. If it does not, then inspect another. If none appear to fit well, then try combining two or more of the simple models and repeat the process.

In principle, you can always improve the fit of a model by making it more complex (i.e. by increasing the number of parameters). In practice, however, you have to compromise between simplicity and goodness of fit. One way of arriving at a compromise is to calculate the Akaike information criterion (AIC) and choose the model for which the AIC is least. The AIC is defined as (Equation 23.11):

$$\text{AIC} = -2 \times \ln(\text{maximised likelihood}) + 2 \times (\text{number of parameters}). \quad (\text{Eqn 23.11})$$

Any given experimental variogram has a variable part (Equation 23.12):

$$\hat{A} = n \ln R + 2p, \quad (\text{Eqn 23.12})$$

where n is the number of experimental values, R is the mean squared residual and p is the number of parameters. Fitting by least squares minimises R , but if it is diminished only by an increase in p (n is constant) then there is a penalty, which might be too big.

4. Check that the model you choose accords with prior knowledge. If it does not, then investigate further. You might need to shorten the interval between successive lags, narrow the angular discretisation, or change the maximum lag to which you fitted the model. If none of these proves satisfactory, then think whether there is some, probably non-random, component in your data that you have not recognised. As above, you should seek professional advice.
5. Tabulate the values of the parameters of your chosen best-fitting model. You will need the values for kriging (see *Kriging: spatial estimation or prediction*).

Software for model fitting

Most authorised models for variograms are non-linear in their parameters, and so ordinary least-squares regression techniques cannot be used to fit them. Instead, solutions must be sought by iteration with a numerically sound program. If you are not yourself a competent numerical analyst, or cannot call on one for help, then you should use a well-tried professional statistical program. GenStat (2006) and S-Plus (Mathsoft Engineering and Education (2006) have the necessary facilities, including commands for fitting the popular models, and are recommended. Treat amateur programs with great caution.

An alternative hybrid approach is that of Pannatier (1996) in his program Variowin. Here, you compute the experimental variogram and display it on the screen. You then fit a model by eye, and as you do so the program calculates a goodness-of-fit criterion based on the sum-of-squared deviations between the model and experimental values. You then adjust the parameters of your model in an attempt to improve the fit while the program recalculates the goodness-of-fit criterion and keeps a tally of the parameter values that minimise the criterion. You might not find the optimum fit, but you should get close. You are restricted, however, to the few models in the program; they are the popular power, exponential, Gaussian and spherical functions.

Kriging: spatial estimation or prediction

The kriging process estimates, or predicts in a spatial sense, the values of z at unsampled places or 'targets'. An ordinary kriged estimate is a weighted average of data. So, if you have data $z(\mathbf{x}_1), z(\mathbf{x}_2), \dots, z(\mathbf{x}_N)$, then the estimate at a target point $\mathbf{x}_0$ is formed as (Equation 23.13):

$$\hat{Z}(\mathbf{x}_0) = \sum_{i=1}^N \lambda_i z(\mathbf{x}_i). \quad (\text{Eqn 23.13})$$

The quantities λ_i $i = 1, 2, \dots, N$, are the weights. These sum to 1 so that the estimate is unbiased, and subject to this condition the weights are chosen to minimise the estimation variance, given by (Equation 23.14):

$$\begin{aligned} \text{var}[\hat{Z}(\mathbf{x}_0)] &= E[\{\hat{Z}(\mathbf{x}_0) - Z(\mathbf{x}_0)\}^2] \\ &= 2 \sum_{i=1}^N \lambda_i \gamma(\mathbf{x}_i, \mathbf{x}_0) - \sum_{i=1}^N \sum_{j=1}^N \lambda_i \lambda_j \gamma(\mathbf{x}_i, \mathbf{x}_j). \end{aligned} \quad (\text{Eqn 23.14})$$

In this equation $\gamma(\mathbf{x}_i, \mathbf{x}_j)$ is the semivariance of Z between the data points $\mathbf{x}_i$ and $\mathbf{x}_j$ and $\gamma(\mathbf{x}_i, \mathbf{x}_0)$ is the semivariance between $\mathbf{x}_i$ and the target point $\mathbf{x}_0$. It is minimised by solving the kriging system of equations (Equation 23.15):

$$\begin{aligned} \sum_{i=1}^N \lambda_i \gamma(\mathbf{x}_i, \mathbf{x}_j) + \psi(\mathbf{x}_0) &= \gamma(\mathbf{x}_j, \mathbf{x}_0) \text{ for all } j \\ \sum_{i=1}^N \lambda_i &= 1. \end{aligned} \quad (\text{Eqn 23.15})$$

The quantity $\psi(\mathbf{x}_0)$ is a Lagrange multiplier. Solution of the kriging system provides the weights, which you insert into Equation 23.13 to obtain your estimates. In addition you obtain the kriging variance as (Equation 23.16):

$$\sigma^2(\mathbf{x}_0) = \sum_{i=1}^N \lambda_i \bar{\gamma}(\mathbf{x}_i, \mathbf{x}_0) + \psi(\mathbf{x}_0). \quad (\text{Eqn 23.16})$$

You can estimate z over larger blocks, B , in the same way. The equations are only a little more complex. The estimation variance to be minimised is (Equation 23.17):

$$\text{var}[\hat{Z}(B)] = 2 \sum_{i=1}^N \lambda_i \bar{\gamma}(\mathbf{x}_i, B) - \sum_{i=1}^N \sum_{j=1}^N \lambda_i \lambda_j \gamma(\mathbf{x}_i, \mathbf{x}_j) - \bar{\gamma}(B, B) \quad (\text{Eqn 23.17})$$

in which $\gamma(\mathbf{x}_i, B)$ is the average semivariance between the data point $\mathbf{x}_i$ and all points within B , and $\bar{\gamma}(B, B)$ is the average of the variogram within B (i.e. the within-block variance). The kriging system is like that of Equations 23.15 with the average semivariances on the right-hand sides, and the kriging variance is obtained as (Equation 23.18):

$$\sigma^2(B) = \sum_{i=1}^N \lambda_i \bar{\gamma}(\mathbf{x}_i, B) + \psi(B) - \bar{\gamma}(B, B). \quad (\text{Eqn 23.18})$$

Choices

Ordinary kriging is the ‘work horse’ of geostatistics; it is robust against departures from assumptions, and it will serve well in 90% of applications. Once you have a suitable model for the variogram it is fairly automatic. There are still choices to make.

Punctual or block kriging

The targets may be points, $\mathbf{x}_0$, in which case the technique is punctual kriging. Alternatively they may be small blocks, B , that may be of any reasonable size and shape but are usually square. The size of block should be determined by the application: over what size of block do you, or your client, want predictions? Choose the size of block by answering this question, not by the data or the cosmetics of mapping (see *Mapping*).

Number of data points

The kriging weights, λ_i , are determined by the configuration of the data in relation to the target in combination with the variogram model. They do not depend on the $z(\mathbf{x}_i)$. Unless the model has a large proportion of nugget variance only the nearest few sampling points carry appreciable weight; more distant points have negligible weight. So kriging is local. This means the N in Equations 23.13 to 23.18 can be replaced by $n \ll N$. Typically n need be no larger than 20; use the 20 points nearest the target. If the data points are exceptionally unevenly scattered, then take the nearest two or three points in each octant around the target.

If you are uncertain how many points to take then experiment with numbers between 4 and 40 and plot their positions in relation to the targets and their weights. Do not be alarmed if some weights are negative, provided they are close to 0.

Transformation

For log-Normal kriging the data must be transformed to $y = \ln z$ or $y = \log_{10} z$, and the variogram model must be of y . If you want estimates to be of z , then the predicted y must be transformed back to z .

Other forms of kriging

As above, ordinary kriging will serve in most instances. It is the least demanding form of kriging, but it takes no account of any knowledge you have apart from the data. Other, more elaborate, forms enable you to incorporate such knowledge. They include the following:

- simple kriging when you know the mean of the process
- universal kriging, which takes into account the trend in $Z(\mathbf{x})$
- the closely related kriging with external drift (also known as regression kriging among pedologists), in which the trend is in a correlated auxiliary variable
- cokriging where both the main variable and auxiliary variable or variables are random
- indicator kriging
- disjunctive kriging, which is especially attractive for estimating the probabilities that true values exceed specified thresholds.

If you have the additional knowledge and wish to use any of these more elaborate techniques, then consult a professional geostatistician.

Mapping

To make a map first kriging at the nodes of a fine grid. Write the kriged estimates and their variances to a file, and transfer it to a congenial mapping program (see below). You may display the results as pixels in colour or shades of grey to represent the magnitudes of the estimates and their variances, or you may thread 'contours' through the grid. Many computer packages for graphics and geographical information systems (GISs) have contouring facilities that will serve. Two popular packages with excellent graphics are Surfer, now in its eighth version (Golden Software (2006) and ArcGIS (widely known as ESRI 2006). Computing the isarithms involves another interpolation, and this is rarely optimal in the same way that kriging is. However, if the kriged grid is fine enough, this lack of optimality will not noticeably degrade the map. In most instances kriging at intervals of 2 mm on the finished map will be adequate.

Do not use graphics programs or GISs for the geostatistical analysis unless you are in complete control and you know they do exactly what you want.

In addition to contouring the kriged estimates, you should map the kriging variances or their square roots, the kriging errors. A map of either of these will give you an idea of the reliability of the map of estimates. In general it will show the largest errors where sampling is most sparse and where you might need to sample more.

The grid interval need not be related to the block size if you block kriging. The blocks may overlap, or there may be gaps between them.

Creating a fine grid of kriged values can place a heavy load on a computer, mainly because of the matrix inversion. You might think of lightening the load by working with a single matrix **A** that contains all the semivariances between the data points and inverting it just once. This is unwise or even impossible if the matrix is very large. Rather, you should keep the matrices small such that points that carry virtually no weight are excluded. Effectively this means kriging in a moving window. You can judge the size of window or size of matrix by examining the kriging weights for a few examples. In general, the smaller the nugget variance in relation to that of the correlated variance or sill the more concentrated is the weight close to the target and the fewer data points are needed for the kriging. As above, n rarely needs to exceed 20.

Sampling

Although any geostatistical analysis must be preceded by observation at sample points, the way in which those sample points are arranged in the field is best decided in relation to the demands of the analyses.

Whereas classical statistics demands some degree of randomisation for unbiased estimation with known variances, in geostatistics randomness is built into the underlying model of the generating processes. It is unnecessary, therefore, to incorporate random selection in the sampling design. The practitioner should not intentionally bias the selection, but otherwise adequate coverage is more important. There are two demands, one for the variogram and the other for the kriging.

Sampling to estimate the variogram

Choosing a sampling scheme for the variogram has three aspects.

1. The maximum lag distance should be such as to embrace most of the spatial variation in the region.
2. The lag interval should be small enough and the number of increments large enough for estimates to reveal the form of the function.

- 3. There should be sufficient data to provide reliable estimates of the semivariances for several nominal lags between zero and the maximum lag distance.

The first may be judged from prior knowledge, from visible features in the landscape or from general understanding. If none of these help, then you might have to make a prior reconnaissance by nested sampling and a hierarchical analysis of variance of the data to determine roughly the spatial scale of the variation. Webster and Butler (1976) designed such a scheme and were the first to compute experimental variograms with it. The technique is now part of geostatistical repertoire (described fully in Webster and Oliver 2001). The second depends to some extent on the first in that you should aim to have semivariances estimated at ten or more lag distances between zero and the maximum lag distance in each direction. If you require the variogram solely for kriging, then you should estimate it accurately at the shorter lags. For kriging, a regular grid is generally best (see *Sampling for mapping by kriging*) but a strict grid with a large interval might not enable you to estimate the variogram at these short lags. Practitioners recognise this, and they elaborate their grid sampling by adding points at closer spacings at some of the grid nodes. Figure 23.5 shows two examples in which additional points are placed on the grid lines. In Figure 23.5(a) the additional points are 0.1 and 0.3 units away from a grid node, and this enables one to compute semivariances at lag distances 0.1, 0.2, 0.3, 0.4, 0.6, 0.7 and 0.9 units on the principal axes. In Figure 23.5(b) the additional points are 0.2 and 0.4 units from the grid nodes, and with this design you can compute $\bar{\gamma}(h)$ at lag distances 0.2, 0.4, 0.6 and 0.8 units. Alternatively, you can impose a nested scheme of the kind introduced by Webster and Butler (1976) at a subset of the grid nodes. Atteia et al. (1994) implemented such a scheme for a survey of trace metals in the soil of the Swiss Jura.

The third aspect of choosing a sampling scheme (item 3 in the list) is widely misunderstood. The classical formula for the confidence interval of a variance does not apply to the variogram as calculated by Equation 23.5. The same data are used many times over, and successive estimates are correlated. Further, the widely promulgated notion that only 30 to 50 paired comparisons [$m(\mathbf{h})$ in Equation 23.5] are needed is seriously misleading and leads to poor estimates and erratic experimental variograms. It is now understood from empirical studies that 150 to 200 data points on a grid will usually give reliable estimates if variation is isotropic and that 100 points should be regarded as a minimum requirement. If variation is anisotropic (i.e. variation depends on direction), then many more points are likely to be needed to estimate the anisotropy.

Sampling for mapping by kriging

If you are making a map from data, you usually will want even coverage, and you should therefore sample using a grid. A triangular grid will give the most precise estimates for a given

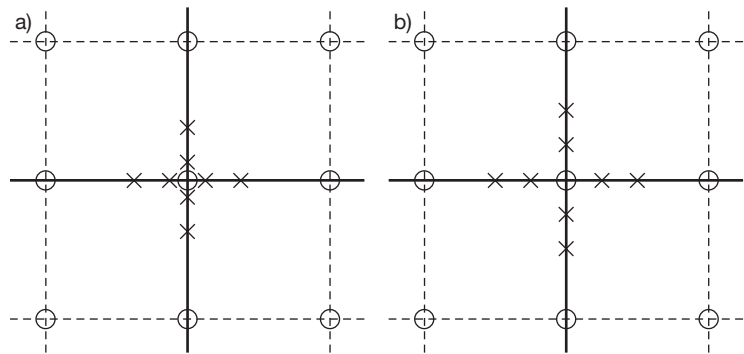


Figure 23.5 Two designs for supplementary sampling on a square grid for the estimation of the variogram. The circles are the grid nodes, the crosses are the supplementary points.

sample density, but a rectangular grid is more practicable and only slightly less efficient. If the variation is isotropic, the grid should be square, and all that remains for the practitioner to decide is the grid interval. If the budget is fixed, then that determines the number of sampling points that can be afforded, and the grid interval follows. If, however, a client specifies the quality of the map in terms of tolerance of estimates about the true values, then the variogram can be used to determine the grid interval as described by McBratney et al. (1981) with the program of McBratney and Webster (1981).

For punctual kriging you proceed as follows.

1. Set up the kriging equations for a square configuration of sampling points with the target point at the centre.
2. Solve the kriging equations for the smallest sampling interval likely to be of interest and obtain the kriging variance.
3. Increase the sampling interval in steps and repeat the calculations at each step.
4. Draw a graph of the kriging variance (or its square root, the kriging error) against sampling interval and link the plotted points by a smooth curve.

You can then read from this graph the sampling interval corresponding to the tolerance expressed as variance (or error). You simply draw a horizontal line at this variance to cut the curve, and by dropping a perpendicular from the intersection you obtain the sampling interval. That will determine the number of sampling points and the budget.

For block kriging you follow the same sequence of steps, only now you must place the target block in two positions, one centred in the grid cell as above, and the other centred over a grid node. The reason for the second position is that the maximum kriging variance can occur there for some combinations of block size and grid interval, and you want to know the maximum kriging variance. Webster and Oliver (2007) describe the procedure and show examples.

The client might specify an average error rather than a maximum. In that event, in step 2 you can place the target point or block at numerous positions at random within the grid, compute the kriging variances at those positions and then average them. If you choose to work with the kriging errors, you should average the variances before taking the square roots – the variances are additive whereas their square roots are not.

Inspecting data

Once you have your new data you should inspect them before you do the analyses described above. See *Chapter 21* for instructions on most of the do's and don'ts in exploratory data analysis, but it does not, however, deal with spatial distributions. Although you should examine the spatial distribution of any variable before you embark on formal analysis, you cannot do that until you have the data, thus the discussion here.

Once you have removed or corrected wrong values, dealt satisfactorily with outliers, and transformed your data to stabilise variances you can explore the spatial distribution of z . Start by making maps. For data on grids these can be pixel maps with colours or shades of grey to indicate the magnitude of z . Alternatively, and for irregularly scattered data, make a preliminary isarithmic ('contour') map. Employ a reputable program with a well-behaved algorithm for interpolation, such as inverse-squared-distance weighting or simple bilinear interpolation if the data are dense, and use layer shading to indicate magnitude.

Examine the map for trends and patches. If there are patches but no evident trend, then you can proceed to analyse your data by the techniques described above. The diameters of the patches will roughly equal the range of the variogram. If patches elongate in much the same direction, then variation is anisotropic, and you will need to estimate the variogram in several directions and fit an anisotropic model to the results.

If there is an evident long-range trend over the region, identify its form and principal direction. Long-range trends are incompatible with the assumptions of stationarity on which the techniques above are based; therefore a model for z that incorporates the non-stationary trend needs to be adopted. This will take you into more advanced techniques, and you should consult a specialist about it.

Software

I have already advocated GenStat and S-Plus for fitting non-linear models to variograms. The same software will enable you to do all the other analyses mentioned above. In addition to the pre-programmed macros which you can call, both have languages that enable you to write your own programs. The library of geostatistical routines in GSLIB (Deutsch and Journel 1998) contains Fortran subroutines for forming the experimental variogram and for kriging. It does not have facilities for the model fitting, however. The professional program Isatis (Geovariances 2006) also has facilities for standard geostatistical analyses and many others. It has a fixed menu, however, and no programming facilities.

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Analysing uncertainty

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Introduction

It is not sufficient for land resource surveys to produce just maps showing predictions of soil classes, attributes or various interpretations – the uncertainty of each prediction should also be shown. This additional requirement becomes indispensable when the data are used for simulation modelling (see *Chapter 28*). Uncertainty analysis provides answers to the following questions:

- ▶ how good is the prediction?
- ▶ which variables are the most sensitive?
- ▶ where we can spend the available resources to reduce the uncertainty of the results?

Despite its importance, uncertainty has been seldom quantified in routine survey and land evaluation. Partly, this is because survey agencies are unaware of what to do in a fairly complex field. This chapter introduces the topic and guides agencies in the steps they can take.

Analysis of uncertainty in laboratory measurement is well documented (e.g. Allmaras and Kempthorne 2002). However, there are differences between the uncertainties encountered during assessment of land resources and laboratory data, the main difference being the source of error. In the laboratory, the measure of uncertainty is obtained from replicated measurements under controlled conditions, and the variation is attributed to random error. In models, identical outputs are expected when the same inputs are fed into a deterministic model. The uncertainty of the output can be quantified by treating the inputs as random variables. Thus, the outputs of the model will be random because they are transformations of random inputs (McKay 1988). This chapter deals with uncertainty in models, whether they be pedotransfer functions, statistical models for spatial prediction, environmental predictors or simulation models.

Several terms such as *error*, *deviation*, *uncertainty*, *sensitivity*, *risk* and *reliability* have been used interchangeably and, it has to be said, carelessly. Each has a specific meaning and to prevent further confusion and misunderstanding they are defined formally (Table 24.1). McBratney (1992) recognised three types of uncertainty in soil information: stochastic, deterministic and semantic. Stochastic uncertainty has been the focus in statistics and probability theory, deterministic in chaos theory and semantic in fuzzy theory. This chapter will only deal with the first type of uncertainty, stochastic.

Uncertainty is a major topic in the spatial information sciences, and there are good monographs on it. Heuvelink (1998) provides a theoretical description and supplies applications of uncertainty analysis in geographical information systems (GISs). Zhang and Goodchild (2002) discuss the theoretical aspects of uncertainties in geographical information and how to deal with various types of error in modelling them. Foody and Atkinson (2002) review the theory and practical applications of uncertainty analysis in remote sensing and GISs. The same reference

Table 24.1 Definitions relating to uncertainties associated with predictive models – compiled from Everitt (2002), Olea (1991) and Robinson (1999)

Term	Definition
Error	The difference between the quantity obtained by a model and the true value
Precision	A measure of variability of the prediction to the true value
Bias	The average deviation of the prediction from the true value, characterised by mean error
Accuracy	A measure on how close the prediction is to being correct. An accurate prediction has no bias and high precision. Inaccuracy is usually quantified by the root-mean-square error. $\text{Inaccuracy}^2 = \text{bias}^2 + \text{imprecision}^2$
Uncertainty	Lack of assurance about the truth of a statement or about the exact magnitude of an unknown parameter
Risk	The chance or possibility of suffering loss as a consequence of uncertainty. Risk refers to situations where it is possible to indicate the likelihood of the realised value of a variable falling within stated limits. In contrast, uncertainty refers to situations when this value cannot be expressed in terms of specific mathematical probabilities
Uncertainty analysis (or error analysis or error propagation)	A method for assessing the variability in an outcome variable that is due to the uncertainty in estimating the values of the input variables or model parameters
Sensitivity analysis	Extends uncertainty analysis by identifying which input parameters are important in contributing to the predicted imprecision of the outcome variable. Consequently, a sensitivity analysis quantifies how changes in the values of input parameters alter the value of the outcome variable
Reliability	The extent to which the same measurement of individuals obtained under different conditions yield similar results
Confidence interval	An interval so constructed as to have a prescribed probability of containing the true value of an unknown parameter

includes a valuable foreword by PJ Curran on the concept of uncertainty. Assessing the accuracy of spatial data is reviewed by Foody (2001). A special issue of the *International Journal of Geographical Information Science* deals with statistical approaches for dealing with uncertainty (Heuvelink and Burrough 2002).

Analysis of uncertainty is a major topic in many other branches of science (May 2001; Giles 2002). Confidence limits need to accompany predictions, and uncertainty needs to be clearly communicated. Moreover, there are always limits to knowledge and understanding of any system. In many cases the uncertainties in scientific advice to policy-makers are not due to random errors attached to predictions, but revolve around a fundamental lack of understanding (May 2001). Hoffmann-Riem and Wynne (2002) stress the distinction between uncertainty and ignorance – risk assessment emphasises limits to knowledge, rather than proving existing knowledge to be more or less correct.

Components of uncertainty

Digital soil mapping describes spatial variation in various ways. Make sure the associated uncertainties are accounted for when using models of any kind for predicting properties, interpreting land suitability, or simulating soil and landscape processes. Uncertainty in a

model's support arises from two main sources: input variables and the model itself. The first is due to measurement errors and approximate knowledge of the true values (i.e. sampling fluctuations); the second is caused by misrepresentation, usually oversimplification, of the true processes. Errors in each component propagate through to the final output.

Simulation models (see *Chapter 29*) are often used to explore scenarios. These models usually require as inputs many parameters and boundary conditions. The parameters are estimated from direct measurement or inferred from existing data (e.g. clay content from a soil map, rainfall from climate data). Although spatial variability is ubiquitous and widely acknowledged, it is often ignored in simulation studies. Brazier et al. (2000) give an example relating to hydraulic conductivity, which typically displays variation of at least an order of magnitude for a single land unit (Nielsen et al. 1973; Warrick and Nielsen 1980), and yet the term is often represented in models by one number. Where background studies are lacking, assignments need to be made about basic characteristics such as soil type or soil texture, and this subjective judgement increases uncertainty. The model structure itself can also be a source of uncertainty, as it reflects the necessarily incomplete understanding of the processes present in the system being modelled (Brazier et al. 2000).

Assessment of uncertainty

To gauge the uncertainty of input variables and models, either analytical solutions or Monte Carlo simulations can be used. These two methods require probability distributions of the input variables or parameters of the model. For quantifying the uncertainty of the model, analytical solutions can be applied when the model is linear, otherwise the more general method of bootstrapping is required. As noted earlier, the model might be a pedotransfer function, an empirical relation (e.g. the Universal Soil Loss Equation) or an environmental predictor (e.g. a terrain attribute).

Analytical form

One common approach is based on an analytical solution of the model, such as the so-called first-order Taylor analysis. This is based on estimating the partial contribution of the error in each variable and evaluating its contribution to overall uncertainty. The mathematical model used, usually known as error propagation, assumes that a model y is a function of inputs x , that is, $y = F(x_1, x_2, x_3, \dots)$. Based on calculus, the variation in y can be calculated from (Equation 24.1):

$$\text{var}(y) = \sum_i \left(\frac{\partial F}{\partial x_i} \right)^2 \text{var}(x_i) + 2 \sum_{i,j} \left(\frac{\partial F}{\partial x_i} \right) \left(\frac{\partial F}{\partial x_j} \right) \text{cov}(x_i, x_j). \quad (\text{Eqn 24.1})$$

One of the common examples in using this approach is in analysing the effect of the uncertainty in the components of the Universal Soil Loss Equation on the final prediction of soil loss (e.g. McBratney 1992; Burrough and McDonnell 1998; Biesemans et al. 2000). Burrough and McDonnell (1998) presented theory with examples on the use of first-order error analysis. Heuvelink (1998) reviews analytical techniques and their application to GISs in detail.

First-order and other analytical techniques require that a model be expressed in a mathematical form and is able to be differentiated, and such a model can be difficult or impossible to define (e.g. for a crop simulation model where the predictions of yield are generated by interacting submodels relating to water availability, nutrient supply and physiology). The linear assumption and truncation of the higher-order terms of the Taylor expansion limit the occasions when analytical solutions can be applied. Furthermore, the use of higher-order expansion

(e.g. second-order analysis) and incorporating correlation among variables can result in very involved equations that are hard to program.

Monte Carlo simulation

A general method of quantifying uncertainty is the so-called Monte Carlo method. The term 'Monte Carlo' was coined during the Manhattan Project of World War II: the similarity of statistical simulation to games of chance generated an allusion to the casino in Monaco. The term 'Monte Carlo method' (or simulation) has been broadly used to refer to uncertainty and sensitivity analysis. However, Monte Carlo methods are specifically those in which properties of the distributions of random variables are investigated by use of simulated random numbers (Gentle 1982). Everitt (2002) described them as methods for finding solutions to mathematical and statistical problems by simulation and used when the analytic solution of the problem is either intractable or time consuming.

In the Monte Carlo method, the model is calculated or simulated directly, and the only requirement is that the input variables of the model can be described by probability density functions. Sampling is undertaken repeatedly from the assumed probability distribution of the input variables, and the response of the model is evaluated for each sample. The distribution of the results, along with the mean and confidence interval, can then be estimated. This method is general and does not require any differentiable form of the model. It is therefore well-suited to land resource assessment *as long as surveys provide information on the uncertainty of input variables* (see Chapter 17).

The key to Monte Carlo simulation is a sampling procedure that draws from the probability distribution. The conventional approach is simple random sampling (Cochran 1977, Box 24.1). This yields reasonable estimates if the sample is large (Heuvelink 1998). However, running a simulation model on a large sample might take too long, although with computer processors become faster it could become feasible. For the present, it is necessary to seek methods that reduce the sample size drawn from the distribution while preserving the statistics. Methods such as Latin hypercube sampling (LHS) (McKay et al. 1979) and the sectioning method (Addiscott and Wagenet 1985) have been proposed.

The LHS is a stratified-random procedure that provides an efficient way of sampling variables from their distributions (Iman and Conover 1982). It has been used in soil science and environmental studies, for example, to quantify uncertainty in wheat-production functions (Viscarra Rossel et al. 2001) and soil nitrogen models (Hansen et al. 1999) (see Box 24.2 for the method). Readers are referred to Pebesma and Heuvelink (1999) and Minasny and McBratney (2002a) for more comprehensive theory and application.

A summary of the Monte Carlo method for quantifying uncertainty is as follows.

- ▶ Select input variables and define the likely range for each.
- ▶ Assign probability distributions to each input to represent the variation. Many soil properties can be described adequately by the Normal distribution. Many others, including water fluxes and concentrations of elements, have positively skewed distributions and the log-Normal distribution is often a good approximation to them. Inputs can be considered independently, but in reality many soil properties are correlated, so correlation needs to be considered. Composite variables (e.g. particle size distribution) are correlated to each other and must sum to unity. Default probability distributions for attributes in the Australian Soil Resource Information Systems are tabulated by McKenzie et al. (2005).
- ▶ Devise a scheme to sample the multivariate distribution of soil properties (e.g. simple random or LHS). Again, consider the correlation among the variables.

Box 24.1: Simple random sampling

Simple random sampling involves repeatedly forming random vectors of parameters from prescribed probability distributions. A normally distributed random variable x with mean, μ , and standard deviation, σ , can be generated by:

$$x^* = \sigma r_n + \mu$$

where r_n are normally distributed random numbers with mean 0 and variance 1.

A multivariate Normal distribution with variance–covariance matrix $\mathbf{V}$ can be sampled by the lower and upper triangular matrix (LU) decomposition method (Davis 1987). The variance–covariance matrix $\mathbf{V}$ is first decomposed by Cholesky factorisation:

$$\mathbf{V} = \mathbf{L}\mathbf{L}^T$$

where $\mathbf{L}$ is the lower triangular matrix. To generate the random variables vector $\mathbf{x}$, matrix $\mathbf{L}$ is multiplied by vector $\mathbf{r}_n$ of independent Normal random numbers with mean 0 and variance 1:

$$\mathbf{x} = \mathbf{L}\mathbf{r}_n + \boldsymbol{\mu}$$

The procedure is repeated for sample size n , resulting in a set of variables with expected mean vector $\boldsymbol{\mu}$ and expected variance–covariance matrix $\mathbf{L} \text{cov}(\mathbf{r}_n) \mathbf{L}^T$. Since the random numbers are independent, the covariance matrix $\text{cov}(\mathbf{r}_n)$ equals $\mathbf{I}$ (the identity matrix) and

$$\mathbf{L} \text{cov}(\mathbf{r}_n) \mathbf{L}^T = \mathbf{L}/\mathbf{L}^T = \mathbf{L}\mathbf{L}^T = \mathbf{V}.$$

Box 24.2: Latin hypercube sampling

Latin hypercube sampling involves sampling n values from the prescribed distribution of each of k variables $X_1, X_2, \dots, X_k$. The cumulative distribution for each variable is divided into n equiprobable intervals. A value is selected randomly from each interval. The n values obtained for each variable are paired randomly with the other variables. Unlike simple random sampling, this method ensures a full coverage of the range of each variable by maximally stratifying the marginal distribution. In summary:

- divide the distribution of each variable into n equiprobable intervals
- for the i -th interval, the sampled cumulative probability can be written as:

$$\text{Prob}_i = (1/n)r_u + (i - 1)/n$$

where r_u is drawn uniformly at random from 0 to 1

- transform the probability into the sampled value x using the inverse of the distribution function F^{-1} :

$$F^{-1} : x = F^{-1}(\text{Prob})$$

- the n values obtained for each variable x are paired randomly with the n values of the other variables.

The method above is based on the assumption that the variables are independent of each other, but in reality most of the input variables are correlated to some extent. Random pairing of correlated variables could result in unlikely combinations (e.g. small bulk density with large clay content); furthermore, independent variables tend to bias the uncertainty.

Methods that induce correlation for Latin hypercube sampling (LHS) are discussed in Pebesma and Heuvelink (1999). See also Iman and Conover (1982) and Stein (1987).

- ▶ Choose the sample size, n , depending on the sampling scheme and the number of input variables.
- ▶ Run the model n times using the sampled input variables and each time record the output.
- ▶ Calculate the statistics of the output (e.g. mean, standard deviation, quantile distribution).

Use of Monte Carlo simulation has been hampered by long computation times, especially when many variables are involved (Burrough and McDonnell 1998). However, advances in computing power and more efficient sampling methods have greatly improved their practicality. Easy-to-use software is available: for example @Risk software from Palisade (2000), which is an add-in to Microsoft Excel. Johnson and Cramb (1996) provide an early example of its application to land evaluation in North Queensland.

Bootstrapping

The bootstrap (Efron and Tibshirani 1993) is a general method for assessing the accuracy of a model by generating different models from different realisations of the data. For example, Dane et al. (1986) used the bootstrap to provide confidence intervals for the statistical distribution of soil bulk density in a cultivated field. It was also used to determine the minimum size of sample required to estimate the mean with a selected degree of precision.

Bootstrapping assumes the training data are representative of the population, and multiple realisations of the population are simulated from a single dataset. This is done by repeated 'sampling with replacement' of the original data set of size N to obtain B bootstrap data sets, each with size N . Each bootstrap data set contains different data and the model is calibrated on each of the bootstrap data, resulting in B models.

For example, suppose the training data are $D = \{(x_1, y_1), (x_2, y_2), \dots, (x_N, y_N)\}$. B datasets each of size N are drawn from the training data by sampling with replacement. For each of the bootstrap data sets D^b , $b = 1, 2, \dots, B$, a model $\hat{y}^b(x)$ is fitted. When the model is linear, the parameters of the model are averaged, and the uncertainty of the parameter can be assessed by its standard deviation of the bootstrap sample. However, when the model is non-linear (e.g. a regression tree or neural network), it is better to average the output of the model.

The bootstrap can also be used to enhance a predictive model. This is called bootstrap aggregating or bagging (Breiman 1996), where multiple models are generated from bootstrap samples and the models are aggregated to produce an estimate. The bagging estimate is calculated as the mean of each model (Equation 24.2):

$$\hat{y}_{bag}(x) = \frac{1}{B} \sum_{b=1}^B \hat{y}^b(x). \quad (\text{Eqn 24.2})$$

Reporting uncertainty

The aim of uncertainty analysis is to assess the probability of the output within a certain interval. If one assumes a Normal distribution, one can report the uncertainty in terms of standard deviation, σ . Data are usually stated with $\mu \pm \sigma$, meaning the true value has a probability of 68% of falling in the stated range. A wider confidence interval is usually preferred: for example, the 95% probability which is about $\pm 2\sigma$. In the non-parametric case, the interval can be derived from quantiles of a Monte Carlo simulation (e.g. the 2.5% and 97.5% quantiles approximate a probability of 95%).

In climate modelling, Moss and Schneider (2000) proposed the following terms for confidence bands to describe the certainty of prediction (Table 24.2).

Table 24.2: Terms for confidence bands to describe the certainty of prediction after Moss and Schneider (2000)

Confidence band	Certainty of prediction (%)
Very low confidence	0–5
Low confidence	5–33
Medium confidence	33–67
High confidence	67–95
Very high confidence	95–100

The results of studies on spatial variation (e.g. Beckett and Webster 1971; Wilding and Drees 1983) suggest that it will be unusual for land resource surveys to have more than medium confidence when predicting soil properties at nominated locations.

Uncertainty and sensitivity in prediction

Uncertainty in prediction

The use of pedotransfer functions is increasing because of the demand for inputs to simulation models (see *Chapter 29*). Pedotransfer functions should be applied cautiously because there are many uncertainties associated with the inputs and the functions themselves. Several studies have illustrated the propagation of error through pedotransfer functions and models. For example, Chen et al. (1997) considered the effect of the uncertainty in the input variables for prediction of phosphorus requirements, whereas Leenhardt (1995) and Minasny and McBratney (2002a) calculated the effect of uncertainty in inputs to pedotransfer functions used for modelling the soil water balance. For analysis of uncertainty associated with simulation modelling of soil acidity across Europe, see Kros et al. (1999) – coarse-resolution soil maps were used as input.

Leenhardt et al. (1995) studied error propagation and the effect on simulating crop evapotranspiration (ET). Three main factors contributed to the overall uncertainty:

1. uncertainty in soil data: input data from a fine-resolution map resulted in smaller errors in simulated values of ET compared to inputs from a coarse-resolution map
2. weather and the interaction with the soil's hydraulic functions (see also Minasny and McBratney 2002a)
3. the model's structure: a simple model propagated the uncertainties in soil input less than did a complex model.

Finke et al. (1996) studied the contribution of various sources of uncertainty in input parameters when simulating water and solute transport in a field. For a soil mapping unit in The Netherlands, they quantified the contribution of input parameters to the variability in a model resulting from two major sources of uncertainty: the spatial variation of basic soil properties (e.g. profile composition, soil texture, watertable depths) and the uncertainty associated with the use of pedotransfer functions to predict soil hydraulic properties. They concluded that no single source of variation could explain the uncertainty in calculated behaviours of the soil.

These studies teach us that we must first identify which parameter makes the largest contribution to uncertainty in the results. We might then find ways to reduce this uncertainty. An analysis along these lines (functional sensitivity analysis) will also help decide whether existing pedotransfer functions are sufficiently accurate or whether new measurements are required (Minasny and McBratney 2002b).

Sensitivity analysis

Sensitivity analysis identifies those input variables that have the greatest influence on the outputs. This is of particular importance with simulation models in which there are many parameters and variables. You can assess the sensitivity of an input parameter (or variable) by changing an input and recording the model output (while keeping other parameters constant). Statistical software such as JMP (JMP 2006) can be employed for this purpose.

Nevertheless, Monte Carlo simulation is preferable because it accommodates simultaneous variation in parameter values. Iman and Hora (1990) make the point that if a strong correlation exists between the uncertainties in an input distribution and output distribution then the input distribution is important to uncertainty of the output. The importance of a parameter will be characterised by the goodness of fit (e.g. R^2 value) from a regression between the input and the output.

Sensitivity analysis has been much studied in hydrology and soil physics. Vachaud and Chen (2002) investigated the sensitivity of simulated values of water balance and nitrate leaching to variations in the parameters for transport within a soil class. They found that there exists an 'insensitive' domain in the textural triangle where within-class variability has no effect on long-term simulations – these classes of soil can be defined by a single set of textural parameters. However, there are 'sensitive' texture classes for which accurate estimates of transport parameters are essential. Similar sensitivities exist with interactions between soil hydraulic properties and climate patterns – in some environments, hydrological response (e.g. runoff, deep drainage) will be very sensitive to soil hydraulic properties, but in others climate will be the main determinant.

Spatial uncertainty

Uncertainty in spatial information and its effect on spatial modelling has received considerable attention since the mid-1990s (Mowrer and Congalton 2000). Prior to this, most work was in remote sensing (e.g. Congalton et al. 1983). The data models implemented within most GISs do not consider data uncertainty or error in the data – the implicit assumption is that data are perfect and error-free. In this way, inexperienced users can perform complex analyses while totally avoiding issues of data quality. Uncertainty analysis provides the means to quantify the impact of errors in data inputs and in model structure on the results of analyses. With GISs, this generally results in two data layers: the output and its associated uncertainty.

Two components of uncertainty in spatial data are positional uncertainty (x -, y - and z -coordinates) and attribute uncertainty. The sources of uncertainty can come from errors in measurement, spatial correlation, and mismatch in support (Burrough and McDonnell 1998, chapter 13).

A variogram is commonly used to quantify spatial variation (in terms of separation distance) – it can identify the spatial structure of variation.

Uncertainty in spatial interpolation can be significant (i.e. predicting an attribute value at an unsampled location). The major factors contributing to uncertainty are the points used for interpolation, the number and proximity of the samples, clustering of samples and continuity of the variables (Isaaks and Srivastava 1989). Three ways of quantifying spatial uncertainty are with the standard error in kriging, indicator kriging and simulation.

The usual approach for modelling uncertainty is to compute a kriging estimate and its associated error variance. These are combined to derive a Gaussian-type confidence interval (see *Chapters 21 and 24*, Isaaks and Srivastava 1989). The variogram can also be used to optimise the geometry of sampling (McBratney and Webster 1981).

Non-linear kriging (e.g. disjunctive and indicator kriging) is another method for estimating the probability that an attribute exceeds a value at a specific location. Indicator approaches provide estimates at unsampled locations, as well as the probability that it exceeds a critical

value (e.g. criteria for soil quality or regulatory thresholds in soil pollution). Cattle et al. (2002) demonstrated the method for mapping lead concentration in the inner Sydney suburbs of Glebe and Camperdown. Using multiple indicator kriging they delineated contaminated areas and showed the expected loss that might result from a wrong decision (i.e. declaring safe a contaminated location or cleaning a safe location). The idea is to go beyond a mere assessment of the risk and provide decision-makers with a set of alternative solutions and the corresponding potential costs. See Goovaerts et al. (1997) and Goovaerts (1999) for details and worked examples.

Finally, uncertainty can be described through stochastic simulation (Pachepsky and Acock 1998; Goovaerts 2001). This is similar to Monte Carlo simulation and begins with a set of equiprobable representations (realisations) of the spatial distribution of soil attribute values. Differences between simulated maps are used as a measure of uncertainty. Many algorithms are available (see Goovaerts 1997). A model or given scenario (fertiliser application, remediation process, land use policy) can be applied to the set of realisations, and they allow the uncertainty of the response (crop yield, remediation efficiency, soil productivity) to be assessed.

Conclusions

The focus of prediction is shifting from the mere estimation of unknown values towards estimating the uncertainty associated with any prediction. The effort required to learn and apply these techniques is well worthwhile. The methods result in three main benefits:

1. they identify inadequacies in our modelling of a process or attribute
2. they identify where and what input variables need to be improved
3. most importantly, they indicate the confidence we have in our final results.

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Information management

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Introduction

Information management includes all activities that allow us to record, access, use and maintain information. Without it, the full benefits of land resource surveys cannot be enjoyed. Poor management can result in:

- loss of data and information
- duplication of data
- poor quality or incorrect data
- much pre-processing and manipulation of data to make them useable
- ignorance of particular data.

The Australian National Land and Water Resources Audit (NLWRA) concluded in 2002 that long-term and systematic investment in natural resource data reduces the cost associated with finding, restoring and collecting data (NLWRA 2002). Resources freed can be redirected to fill serious gaps in knowledge.

Information is an asset. Compared to more obvious physical assets, it is often overlooked. Land managers use information – a *conceptual asset* – to manage their *physical assets*; recognising information as a tangible asset is a step towards allocating an appropriate level of resources to information management. The Australian and New Zealand Land Information Council (ANZLIC) have published the *Natural Resources Information Management Toolkit* (NLWRAAN-ZLIC 2003) to assist with best practice.

Data need custodians who exercise their responsibilities. Often the custodian is the state or territory agency responsible for land resource survey. Custodians have responsibilities to ensure information moves from projects (e.g. survey databases) to consolidated collections (e.g. publicly accessible information systems). Organisations must be committed to their roles as custodians and assign resources to maintain, update and provide access to sets of data and authoritative products from them.

Land resource information systems have been in use for more than 25 years (e.g. Bie 1975; Moore et al. 1981) but advances in technology have had a major impact on the approach of both individuals and organisations (Galliers and Leidner 2003). Use and integration of information in digital formats have increased dramatically in recent years. The technology is no longer the limiting factor in many instances. More often the intangible aspects of information management limit effective use of the resource.

Information management has technical, intellectual, economic and sociopolitical aspects. While knowledge forms the currency for managing land and water, there is a risk that too much information can impair our ability to integrate and assimilate knowledge. It is important

to be able to identify and to efficiently extract information relevant to our purposes. For this reason information management is the key to success.

In Australia, all government jurisdictions have agreed on a set of principles to improve coordination of information and to develop an Australian Spatial Data Infrastructure (ASDI) (ANZLIC 2003). These principles include the following.

- ▶ *Governance.* Holders of spatial data, service providers and users in government agencies, business enterprises, academic institutions and community groups are involved in implementation and use of the ASDI.
- ▶ *Data access.* Users of spatial data are able to find and access data and services with few if any impediments.
- ▶ *Data quality.* Users can easily ascertain the quality of spatial data and their fitness for purpose.
- ▶ *Interoperability.* Access to, and combination of, spatial data and services are made efficient for users through the use of the best technologies for interoperability.
- ▶ *Integratability.* Spatial data conform to common standards that enable integration with other data, so that they can be used effectively.

Although most data have spatial context and can, therefore, be considered under the scope of this agreement, in practice it has been limited to maps and similar resources.

Good information management needs to identify:

- what data should be kept
- how to organise the data
- where they should be held
- who should have access to them.

The following sections use these categories to describe the practices and processes of information management for land resource assessment.

Identifying data to keep

The NLWRA (2002) recognised seven fundamental types of data sets for assessment and analysis in agricultural production, environmental monitoring, biodiversity and natural resource management. These types were: land use, soil properties, dryland salinity, native vegetation, water resources, river condition and estuaries. Clearly, land resource assessment is a major contributor. NLWRA (2002) suggests that these data sets be updated nationally at least every five years and used to report on the state of the environment. It further acknowledged that these data sets need programs for maintenance and management if they are to continue to support planning, management and user requirements.

Surveys generate large amounts of data and information, some in draft form. This will need to be reviewed and the most beneficial retained in an accessible form.

Long-term management of land resource data requires significant investment. It should not be restricted to the end of a project and assumed it will happen automatically. At the start of a project specify how information will be managed (see *Chapter 14*), who will do it and provide the resources.

Types and sources of data and information

In conventional survey, surveyors rely on the following forms of information at the beginning of an investigation:

- maps, reports, existing site descriptions and local knowledge
- topographic maps
- air photographs
- satellite imagery.

Surveyors use these to define land types and to choose sites for sampling and verification; they also use them to create mental models of the landscape. Commonly these complex models are not recorded. The advent of quantitative methods has resulted in a much wider range of data and information being used. These include:

- surface reflectance images from satellites and airborne scanners, including high resolution and hyperspectral images (see *Chapters 11 and 12*)
- digital elevation models (DEM) and derived surface attributes (e.g. slope, curvature, relative elevation, flow accumulation and topographic wetness index – see *Chapter 6*)
- geophysical images including gamma-ray spectrometry (radiometrics), magnetic and electromagnetic conductivity data (see *Chapter 13*).

The new methods have placed new demands on information management and analysis. Increasingly, survey teams need specialists in geographical information systems (GISs) so that spatial data can be used to their full potential. It is important to document the models used for spatial prediction of land attributes. Even with the expansion of new information sources, there are two basic types of information for land resource assessment:

- 1 *spatial information*, describing the location of, and relations between, objects in the physical world
- 2 *non-spatial information*, referring to other data (besides location) that describe characteristics and behaviours of these objects (including models).

Most information has value, and it is not just a project's final products that require management. Often the pieces of information acquired throughout the whole process of a land resource assessment are valuable for further work. Most significant for conventional surveys are:

- field sheets and notebooks
- annotated maps
- air photographs
- field photographs.

These are usually bulky and require considerable storage space, but they are essential and valuable historic records.

Increasing use of digital technologies in survey produces a wide range of information that needs be managed, including:

- databases and spreadsheets
- documents
- images
- spatial coverages
- models and their outputs.

Digital information, while conferring many benefits, can be more difficult to manage. Computer files are easy to misplace, lose or delete. File names and directory locations are often not meaningful except to their creators, and human memory fades with time. Models or GIS mapping projects can quickly become defunct if some of the data are moved or deleted, or as computer operating systems, hardware and software are updated. Any project team must

ensure that the information it collects and generates is well maintained, accessible and useable by future users. Changes in storage technology (e.g. cards to tapes to floppy disks to CD/DVDs and solid-state storage) threaten access to data.

Information as part of the survey

Information is acquired throughout the life of the survey, and in some cases before and after. Traditionally, much has been in cumbersome hardcopy form. With the advent of computers, it has become much simpler to share and integrate data – for example, where one copy of a particular report may have been available to a survey team, now digital copies can be easily made and distributed.

The GISs, databases and complex computer models are useful throughout the survey. All too often these are not available to field staff and they are used only for final maps and reports. Their power arises from their capacity to capture, accumulate and visualise data, to model landscape processes and to re-run analyses. They help surveyors to understand landscape processes which may lead to modified field sampling of poorly understood situations. Their use throughout a survey can assist in distributing limited effort efficiently and effectively.

Minimum data sets

The benefits of surveys accrue as they progress, and remain afterwards, but the main costs are incurred at the time of survey itself. Therefore, ensure information of lasting value is gathered at this stage. Long-term benefits arise from strict adherence to standards for minimum data sets (see *Chapter 17*). This ensures integration of compatible data for future research or to produce synoptic overviews. Minimum data sets for land resource survey in Australia are defined (see *Chapter 17*).

Organising information

Collection standards

In the 'Field handbook', McDonald et al. (1990) define soil and landscape attributes and give standard codes and descriptions. It is the standard for Australia, even though it has some limitations. Analytical standards for chemical (Rayment and Higginson 1992; Rayment et al. in press) and physical (McKenzie et al. 2002) properties are useful standards. These *Guidelines* augment the above standards for measurement by specifying methods for survey design, sampling, selection of variables and procedures for statistical analysis.

Database structures

Most land resource information collected in Australia is entered and stored in databases or spreadsheets. In many instances, data have been committed to databases specifically designed for a project with little consideration of future use, either corporately, regionally or at the state, territory or national level. This invariably makes such data much less useable to other projects and increases the need for further manipulation and reworking. The Australian Soil Resource Information System (ASRIS 2006) makes good many of these shortcomings, and the design of the database can be readily adopted by private or public agencies.

At the agency level, make every effort to create database structures that are compatible with existing ones for land resource information. Build on the national guidelines and standards so that interagency and national reporting can be more efficient (see *Chapters 26 and 32*).

The range of scales and attributes for land resource information is large, and so it is a challenge to define a single standard for a database design. The design for ASRIS (McKenzie et al. 2005) is flexible and can be adapted to contain additional attributes and information as time goes on. As relational databases have become more useable, complex structures for data have been developed to allow the relations of soil entities and their attributes to be recorded better than previously. There are advantages over flat file structures because the redundancy of data is reduced. However, such databases require better understanding by users. A basic fault with many databases designed by land resource survey groups has been the practice of mimicking the structure of data recording sheets used in the field and laboratory in the relational structure of the database. An efficient design (e.g. ASRIS) will not resemble the layout of sheets – instead, it provides the user the intermediate *views* of the database (e.g. as embodied in the format for the data-entry screen or the layout of a plain-English report).

As the technology for analysis of spatial data has developed, so too has the capacity to integrate text and attribute data. Wherever possible, spatial and attribute data should be linked to avoid having to reconnect spatial features to their attribute databases. Otherwise the loss of dependence between the data can lead to the situation where spatial features lose their attributes or where attributes are maintained but without any spatial context. The design for ASRIS is specifically directed towards the integration of data from sites, profiles and spatial locations.

The capacity of databases to store not only spatial features but also other objects (such as images or documents) means that complex and fairly comprehensive data sets can be created. Even at a simple level, land resource databases can contain active links to other datasets, images, web sites and reports.

Databases usually contain coded information to reduce the size of files and also to reduce data-entry requirements. Document the codes and their definitions, and include them with the database. Documentation of database structures, relations between tables and entities, and lists of valid codes with their decoded descriptions are essential if the database is to function over a prolonged period.

Standardised structures, definitions of attributes, and coding must be implemented within agencies to ensure standard analysis and means of delivery. These are essential for integrated assessments at regional, state, territory and national scales (e.g. NLWRA 2002). The benefits of sharing information between agencies are well recognised. As a result, standard templates and documentation for database structures and attributes are starting to be defined for major data sets relating to soil (ASRIS 2006), vegetation (NVIS – see *Chapter 8*) and land use (ALUM – see *Chapter 9*). The data structures in these systems can be used as templates by project teams. The structures simplify implementation of projects and capitalise on existing knowledge.

Standard schemas

The Soil Information Transfer and Evaluation System or SITES (Kidston and McDonald 1997) is based on the 'Field handbook' (McDonald et al. 1990) and has been adopted (and subsequently modified) by many public agencies in Australia. The SITES model is restricted to data from individual sites and does not include information from polygonal or raster mapping. As noted earlier, the ASRIS schema is compatible with SITES but is more comprehensive. Various schemas have been implemented in Australia, and notable examples include the Queensland Soil And Land Information (SALI) database, and the SALIS database in New South Wales.

Data input and entry tools

Most organisations undertaking land resource surveys have proformas for data entry. The use of electronic devices for recording data in the field allows for real-time verification.

Applications on small hand-held devices should have the following programmed features:

- prompt the user for entry of mandatory information
- offer additional information on data and codes, for example, through pull-down lists
- check that the codes given are valid
- allow electronic transfer of data directly into office-based databases via modem, relay on to portable computers with facsimiles of office-based databases, or on return from the field.

This type of data entry and error checking helps prevent the entry of invalid data. The disadvantages of these devices include (see *Chapter 16*):

- susceptibility to damage from water, dust and electric shocks
- attractiveness to thieves
- stored data are vulnerable to loss until downloaded into office databases.

Regularly download data during survey to minimise the risk of loss. If for whatever reason that is not possible, then write them to removable disks that can be stored securely.

Design and test the system for storing and retrieving data before you start survey work. Establish and document procedures for handling normal and exceptional data. Testing should include attempts at data entry where there are known errors to establish the effectiveness of error-trapping processes. Early documentation before fieldwork reduces the risk of spurious data being entered. Regularly update documentation and use it as a basis for metadata records (see *Metadata*).

Field notebooks for systematic recording have risks, because there is no prompting for any information. Notebooks are useful to record exceptional information, and provide an opportunity to describe fully the soil in ways that coded systems cannot. The information recorded in field notebooks is more likely to be reproduced in the text of reports than that in most databases.

Directories and naming conventions

You must have a logical system for arranging entities in computers and ancillary devices, particularly when many discrete and interrelated data are to be stored. The system needs to include specific soil and land information as well as ancillary data used in analysis and display (e.g. information on geology, landform, vegetation, water resources, the cadastre). Logically name directories, subdirectories and individual files. Other users, particularly new or casual users of systems, and yourself will benefit. Standardisation across data repositories within an organisation allows users familiar with one location to interrogate other systems rapidly. It also encourages development of automated processes to locate, analyse and display data.

Attempts have been made to develop standard structures for data directories and naming conventions. However, local needs often override. Obtain advice from experts on the best structures for directories, and consult with staff in all branches of an organisation to ensure that the system is widely adopted.

The Forest Environment Resource Information System (FERIS) implemented in Queensland has a successful standard directory structure – it was subsequently adopted for that State's vegetation information management system. FERIS uses a five-tiered approach for the directory structure including:

- host machine name
- disk name
- geographical extent or theme name

- complement of geographical extent or theme name
- optional subtheme.

Thus, for example //SUNM1/data/vegetation/wettropics/ecosystem/.

Within the specified directory, individual files are named in a similar system that allows immediate recognition of some key information and it uses:

- name
- code for projection
- code for datum
- code for raster cell size or capture scale
- version date.

For example, /regeco5gm0802 would indicate to those familiar with the system a coverage of regional ecosystem data in Zone 55 on GDA94 at a scale of 1:100 000 current to August 2002.

Spatial databases and map projections

The GISs enable you to overlay and analyse spatial information – the ease with which data can be incorporated into digital systems and integrated with other data sets is both a strength and a weakness. These systems rely on spatial data being referenced to a known map projection and coordinate system (see *Chapter 16*).

Ensure the coordinate system and map projection are correctly stated within the metadata record (see *Metadata*) for all sets of data. See *Chapter 16 Navigation and georeferencing* on spatial coordinates and projections. The standards are now the Geocentric Datum of Australia (GDA94), and the Map Grid of Australia (MGA).

The importance of correctly recording the map projection and coordinate system is illustrated by the difference of about 200 m southwest to northeast between the same coordinate in the former AMG/AGD84 standard and the current MGA/GDA94. Users of geographical coordinates (latitude and longitude) should also note that locations have different readings for each datum.

Similarly, while data sets may have identical datum and coordinate systems, the reference base to which they have been recorded might be different and result in non-coincidence of features when overlaid. For example, data registered to a non-survey accurate (Digital Cadastral Data Base) (DCDB) layer may be up to 200 m different from data registered to surveyed ground control or a topographic data set, or a georeferenced satellite image.

Centralised and distributed systems

Much of Australia's land resource information is captured for large government organisations by field operatives distributed throughout country areas. This information has to be collated at higher levels (e.g. state, territory, national, international). As communities' responsibilities for land management increase, it is likely that relevant information will become distributed even further. The wide distribution of centres for data collection, analysis and reporting can create many problems arising from different versions and make quality assurance difficult.

However, the design and capacity of information systems have improved to the extent that truly distributed management of data is possible. Notwithstanding limitations in the capacity of networks, there is no real technical impediment to maintaining a 'single' set of data distributed over two or more locations. Advantages to such a system include local management of locally relevant data, more timely inclusion of updates, and greater access to local knowledge for error checking.

Stakeholders in natural resource data should agree on the location of primary data sets for components or complete themes. ASRIS is an example where state and territory agencies form

the nodes of the revised system. While this may appear daunting, developing a distributed system for capturing data from public and private organisations is even more difficult. Good documentation, incentives for cooperation, and excellent technical standards are prerequisites.

Work is underway across Australia to define and implement information systems that are linked, distributed and interoperable. Such systems rely on agreement and adoption of open standards for linking systems and data. Interoperable systems depend as much on a culture of collaboration within and between agencies as they do on the consistent use of agreed standards (AGIMO 2003).

Metadata

Information about data and information entities is known as metadata. Metadata provides users with information to decide whether the data are appropriate for their needs. Metadata are important for making information useable, especially in the long term when the staff who recorded the data are no longer available to answer questions on, for example, how they were recorded, what methods were used, and their coordinate systems. Record metadata whenever potentially reusable data sets are collected.

Various standards for metadata have been developed and promoted, but there is no general agreement on a preferred scheme. In Australia, standards include ANZLIC II and ISO/TC 211

Table 25.1 Minimum metadata elements required for land resource data

Element	Description
Title	The published name of the data set
Local title	A locally recognised name for the data set
Custodian	The organisation with authority over the data set
Agency position of responsibility	Position within the custodian organisation
Abstract	Brief description of the contents of the data set
Creation date	The date the data set was created
Stored data format	The format in which the data set is normally maintained
Access constraints	Any limitations to access
Data source	Original material contributing to the data set
Intellectual property	Organisation holding rights to intellectual property
Lineage (data history)	Description of how the data set has been created and maintained
Positional accuracy	The level of accuracy of positional/location attributes
Attribute accuracy	The level of accuracy of feature attributes
Logical consistency	The degree to which features within the data set relate to each other (e.g. topology)
Completeness	The degree to which the data set is complete
Standards used for data collection	Any standards in data collection, classification coding and so forth relating to the data sets
Contact name	Contact officer within the custodian organisation for additional information
Projection, map datum and coordinate system	The location reference system used within the data set
Scale	The capture and presentation scales of the data set
Map number	Any reference to published hard copy representations of the data set

19115) for geospatial information. The ANZLIC and ISO19115 metadata models have been modified to incorporate some information within agencies (beyond 'pages 0–1'), and several web-based systems for metadata have been implemented. These allow entry, editing and searching of metadata records and uploading of public records to nodes of the Australian Spatial Data Directory (see *Australian Spatial Data Directory – ASDD*). As a minimum, make sure the metadata elements listed in Table 25.1 are recorded for all land resource data.

Australian Spatial Data Directory – ASDD

The Australian Spatial Data Directory (ASDD) is a component of the Australian Spatial Data Infrastructure (Australian Spatial Data Directory 2006). The web-based data directory has contributions from public agencies and some private organisations across Australia. About 30 000 sets of data are documented in the directory. Beyond providing a directory of data, the ASDD also provides metadata including:

- data description
- data location
- data quality, accuracy and currency
- data lineage (steps in the development of the data set)
- a contact for access to the data
- conditions of access.

While the ASDD is important for the documentation and discovery of useful data, it is still under development, and its use by all agencies is still somewhat limited. NLWRA (2002), in an investigation of entries in the ASDD, found that much of the natural resource information held by public agencies is not documented and that the reliability of the documentation in the ASDD is variable – information management in many organisations requires improvement.

Access to data

Custodianship

Most data recorded during land resource assessment are owned by state, territory and federal governments. The ANZLIC 'Guidelines' (1998) outlines a principle of custodianship that 'assigns to an agency certain rights and responsibilities for the collection of spatial information and the management of this on behalf of the community'. These guidelines are aimed at public-sector custodians but recognise that private organisations can be responsible for public data sets under contractual arrangements. The ANZLIC 'Guidelines' outline seven principles of custodianship:

1. *Trusteeship* – custodians do not own data but hold it in trust on behalf of the community.
2. *Standard setting* – custodians, in consultation, are responsible for defining appropriate standards and proposing them for national ratification.
3. *Maintenance of information* – custodians, in consultation, must maintain plans for information collection, conversion and maintenance.
4. *Authoritative source* – the custodian is the authoritative source for the fundamental data sets in its care.
5. *Accountability* – the custodian is accountable for the integrity of the data within its care.
6. *Information collection* – collection or conversion can be justified only in terms of a custodian's business needs.
7. *Maintain access* – a custodian must maintain access to the fundamental data in its care at the highest level for all users.

Given these custodial rights and responsibilities, information needs to be protected. Digital systems can be readily rendered useless by failure of computer systems, corruption of files, deletion, tampering and incompatibility of different versions of systems and software.

System administrators need to ensure adequate backup for data. This may involve regular duplication of data on storage media or other file systems. Include off-site storage of backup material. Consider the migration of long-term backup or archive material to new media and data formats. Several significant natural resource data sets have been lost in Australia because of inadequate backup.

Data access

The ANZLIC 'Guidelines' deal mainly with the right to establish marketing conditions for fundamental data. They include establishment of formal agreements between custodians and value-adding agencies (either for internal use or the development of new products that can be sold), royalty arrangements, revenue sharing, mechanisms for feedback, copyright and intellectual property.

The Spatial Information Action Agenda (Geoscience Australia 2006) calls for improved access to and pricing of government spatial data, and a copyright policy that maximises the benefits to Australia. The 'Action Agenda' stresses there must be recognition by all levels of government that spatial information forms part of public infrastructure and that spatial data should be made freely available.

Users with an identified requirement should be provided with adequate access to data, whether it is on a closed internal system or on a more publicly accessible web server. However, precautions are needed to ensure integrity of the data at all times.

Access to file systems and individual files must be tightly controlled. This can be at the level of individual users, or groups of users or system administrators. Permissions can be given for reading, writing or executable actions at directory or file levels. In particular, protect the primary data stores maintained on a system from deliberate or accidental corruption, and have separate areas for data analysis well removed from these stores.

Future directions for improved access to information

The responsibility for land resource information is changing to some extent away from state and territory agencies towards regional authorities and community groups. This has blurred the once clear view of natural custodians. This trend has already provided challenges for compilation of integrated datasets such as ASRIS. With more services being provided by the private sector, this devolution is set to continue. The challenge for public and community investors is to develop protocols and frameworks that ensure there is a legacy of data and effective custodians. The NLWRA and ANZLIC have outlined principles and future directions for improved access to information (NLWRA/ANZLIC 2007).

Finally, advances in technology, and the adoption of open standards for the access, delivery, presentation and analysis of data over the Internet, will see wider awareness and demand for natural resource information in the future (see OGC 2005).

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Synthesis studies: making the most of existing data

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Introduction

Information on soil and land resources is required at regional, national and global scales. Compiling this information nearly always involves synthesis of information from studies at finer scales and smaller extents. Many benefits flow from synthesis studies and the information is useful for many purposes (see *Chapter 1*). A surprisingly large number of synthesis studies have been completed recently at regional (e.g. Robinson et al. 2003), state (e.g. Bui and Moran 2001, 2003; Smith 2002), national (e.g. Henderson et al. 2005; McKenzie et al. 2005) and global scales (e.g. van Engelen 2000).

Synthesis studies would be straightforward if we followed the advice of Cocks (1992) to ‘design surveys at all scales as though planning to describe the whole continent, even though this may be never implemented’. The reality is that synthesis studies are difficult and they typically encounter a range of messy problems. The component surveys contributing to a synthesis study commonly are completed at various times, have different objectives, use contrasting methods, are at several scales, and provide incomplete coverage – to name but a few. This chapter discusses synthesis studies and how to make the most of existing data. We draw examples from recent projects in Australia, and refer readers to ALGA/ANZLIC (2004) for guidance on accessing, displaying and managing data in synthesis studies.

Define the new objective

A synthesis study requires clearly defined terms of reference in the same way that a survey does. These specify the objectives that guide all subsequent decisions on data and the choice of methods (see *Chapter 14* for guidelines). Large projects benefit from a pilot study to understand their full scope.

Ascertain what data exist and their custodian

Make sure you understand the quality of existing data and its ease of access. Find what information on land resources is available for the region of interest and obtain access to it as early as possible. Information may include published and unpublished maps and accompanying reports, soil profile descriptions and laboratory data, and data relating to individual land units. Other sources include scholarly studies on soil development and geomorphology (see *Chapter 15*).

The major custodians of land resource information in Australia are the agencies in each state and territory responsible for land resource survey. The Australian Spatial Data Directory (ASDD 2006) is a good starting point for tracing previous work by these agencies. Older surveys are listed in Hallsworth and Archibald (1978) while CSIRO (1983) provides many leads. In addition, there may be data from federal agencies such as CSIRO or from privately commissioned surveys. Some companies have large databases, for example those involved in the fertiliser and mineral exploration industries. Obtaining permission to use such data requires negotiation with the custodian over what the data can be used for and the period for which they are made available. In some cases payment may be necessary, and in others, some agreement over the ownership of the intellectual property of the final product.

Data are valuable and negotiations over licensing require diplomacy and tact. Make sure you recognise the original investment in the data by the custodian or their predecessors, and also appreciate their expectation that the data provide benefits over the long term (i.e. that the data may be old does not lessen their expectation to derive a benefit from it). Benefits to the custodian might be financial, a share of intellectual property in the completed product, or simply recognition of the hard work involved in the original surveys. However, negotiations also need to acknowledge that the long-term value of the data is only realised through its use (e.g. in synthesis studies).

There has been a slow change in attitude among public agencies away from a philosophy that the user must pay again for data already collected at public expense, and towards one where information is supplied at the cost of transfer. The advent of efficient systems for distributing spatial data via the Internet is forcing this cost down to where land resource information is becoming freely available. The Australian Government's policy on spatial data is clear and key aspects of the policy include the following (Office of Spatial Data Management 2006).

- ▶ Fundamental spatial data will be provided free of charge over the Internet, and at no more than the marginal cost of transfer for packaged products and full cost of transfer for customised services.
- ▶ There will be no restrictions on commercial value-adding to the listed fundamental spatial datasets, although each transaction will be subject to a licence setting out the conditions of the transfer.
- ▶ An Internet-based public access system will be developed within the framework of the Australian Spatial Data Infrastructure.
- ▶ The Australian Government will negotiate a multilateral agreement with the states and territories for access to spatial datasets required for Australian Government purposes.

The trend to supplying large data sets via the Internet and the convergence in technologies for managing digital data mean that synthesis studies, rather than being occasional activities at the end of a survey program, will be central to most studies of land resources. This theme is revisited at the end of the chapter.

Collation and checking

Because the data often come from diverse sources, they require collation before they can be used. This involves determining which parts of the region are covered by different types of spatial data, and putting all data into a common database. Johnston et al. (2003) outline the main issues in the first phase of the Australian Soil Resource Information System (ASRIS), and McKenzie et al. (2005) describe the current specifications and database design.

Several mundane but potentially very troublesome problems usually arise at this stage and correcting them is essential but very time-consuming. The major problems are unsuitable

formats for data (digital or otherwise) and the absence or inadequacy of metadata. Synthesis studies sorely test the quality of information management in the original surveys (see *Chapter 25*). Survey organisations need to allow adequate time and resources for data to be properly archived if its long-term potential is to be realised.

When you have compiled the data, assess how much is known about the region. Maps of land resources present different aspects of landscape (e.g. lithology, soils, land systems) and capture the spatial variation of those aspects using different classifications. Determine how much information can be inferred about individual land units. Review the site and profile data and note their sources, the attributes measured, and the methods of measurement. This affects how data and information can be used.

As with the compilation stage, this stage tests the quality of information management in the original surveys, in particular the adequacy of metadata. This stage also tests the quality of reporting for the source surveys and their capacity to impart knowledge.

Map data

The maps collated will usually portray various entities including land systems, soil and soil landscapes. In all of these, soil distribution is described with respect to landform, geology and vegetation. In many cases, the landscape models used by the original surveyors can be used to disaggregate soil associations and reallocate individual soil types to portions of landscapes (as was done for the study of the Murray–Darling Basin) (Bui and Moran 2001, 2003). This depends on the models of the relationship between soils and landforms in the landscape being adequately reported through descriptions of the map legend and landscape block diagrams (see *Chapters 18* and *32*). Where maps are presented with data in a series of spreadsheets but without an accompanying report or block diagram (e.g. Rogers et al. 1999), disaggregation procedures can be applied only with involvement of the original surveyors.

Source maps use many different classification systems for soil and land. It may be possible to choose one classification system for the synthesis study and reclassify source maps using the preferred system. Bui and Moran (2001, 2003) selected the Factual Key (Northcote 1979) as the common classification system.

For large regions, however, this seemingly simple step can become overwhelming. For example, allocation of soil profiles to the Australian Soil Classification or World Reference Base becomes a major cost when more than a few thousand profiles are involved. Furthermore, allocating profiles with these systems requires data that were not recorded in past surveys and simple translations between classification systems (e.g. Factual Key to the Australian Soil Classification) are not reliable.

Cartographic scale is not always a good indicator of survey effort per unit area. Some maps in Australia at 1:100 000 are little more than a reconnaissance effort whereas others have a solid basis with extensive field observations and supporting laboratory data.

Soil profile and site data

The quality of point data for a region can vary enormously because the data may have been collected over a long period, by different agencies with different methods, and for different purposes. Most large soil databases in Australia have data of various quality and the most notable problems arise with positional accuracy, detail of the profile description and extent of laboratory characterisation. Most records have morphological descriptions of the profile. Many have data on soil texture and pH. There are few other chemical data and soil physical data are uncommon. Table 26.1 is a summary of the soil horizons in the database compiled for the first phase of the Australian Soil Resource Information System.

Table 26.1 Number of soil profiles from each state and territory held in the ASRIS database

	State/territory	CSIRO	Total
NSW	23 920	499	24 419
NT	4717	108	4825
QLD	37 884	2246	40 130
SA	20 806	1522	22 328
TAS	5043	275	5318
VIC	3787	399	4186
WA	60 593	775	61 368
ACT	0	1456	1456
Total	156 750	7280	164 030

Observations recorded in existing Australian databases generally have an unknown degree of bias (see *Chapter 20*). In some cases, the data may reflect the effort spent resolving boundary issues or unusual features rather than characterising the dominant soil. For example, out of 2531 points available for the Dalrymple Shire in North Queensland, 1301 had a reported soil type that matched the dominant or codominant ones for that land unit; 654 points had a reported soil type that matched one of the minor ones for that land unit and 576 points had a reported soil type that did not match any of those for that land unit. Similarly, sampling in some regions is targeted on roadside reserves (to maximise the rate of survey) and so the results may not provide an accurate estimate of soil conditions under adjacent farmed land.

Failure by surveyors to use standard methods can undermine the data's usefulness. Soil profile databases in Australia display various inconsistencies in the way soil horizons are described and named, despite the existence of an agreed standard for horizon description (McDonald et al. 1990). In some cases, horizon designators are missing, and in others obsolete terms are used. Similarly, allocations to soil classifications are often inconsistent or missing. This constrains the degree to which data from different profiles can be compared. These problems are being slowly remedied as experience with synthesis studies increases. Data entry is a common source of error and it can result in the following:

- obviously incorrect geographical coordinates (e.g. that plot in the ocean)
- illegal codes for soil classes (e.g. as defined by the Australian Soil Classification)
- measurement units recorded as ppm (parts per million) instead of per cent, or centimetres instead of metres
- no record of analytical method.

The last point is significant. Methods for laboratory determinations of specific soil properties vary and in many cases results cannot be compared directly. For example, in Table 26.2 are listed the methods for pH determination encountered in the first phase of the Australian Soil Resource Information System. Note that no method was recorded for 20% of the data. Only points determined with methods 4A1 (pH of 1:5 soil/water suspension), 4B1 (pH of 1:5 soil/0.01 M CaCl₂ extract), and 4B2 (pH of 1:5 soil/0.01 M CaCl₂ suspension) could be compared directly, since translations exist from pH_{water} to pH_{CaCl₂} (Slattery et al. 1999). A new translation was also developed (Henderson and Bui 2002).

Translations might be neither possible nor sensible, even if adjustment factors are known. Total organic carbon falls into this category. Broadly, two methods for measuring organic carbon have been commonly employed: wet oxidation and with a high-frequency induction

Table 26.2 Number of horizons with laboratory data for selected soil properties in the Australian Soil Resource Information System (ASRIS) database

Attribute	No. horizons	Attribute	No. horizons
Cu	4618	Organic C	43 673
Fe	25 774	N	19 522
Mn	6234	Nitrate	6837
Zn	4786	P	38 386
B	135	Clay (%)	43 699
Al	13 111	Coarse sand (%)	32 011
EC	92 650	Fine Sand	32 264
Ca	44 796	Silt	42 660
K	71 285	Gravel	19 448
Mg	44 846	Bulk density	3724
Na	44 710	Erodibility	3961
CEC	24 194	K _{sat}	515
ESP	4987	K _{unsat}	278
pH	151 810		
Cl	43 498		

furnace. The Walkley–Black method (Walkley 1947) uses wet oxidation and is the most common method in the ASRIS database. However, it does not recover as much organic carbon compared to methods that use a high-frequency induction furnace. Historically, recovery is often quoted in the vicinity of 75–80% (Rayment and Higginson 1992). A correction factor from the incomplete Walkley–Black methods to total organic carbon of 1.3 (i.e. $\sim 1/0.8$) is sometimes offered as a rule of thumb but there is no universal factor. In an Australian study, Skjemstad et al. (2000) detected differences according to the laboratory and the date of analysis, with more recent analyses showing more complete recovery. The appropriate correction factor was notably less than 1.3 and for a large part of the data not needed at all.

The findings of Skjemstad et al. (2000) were difficult to apply to the first phase of ASRIS because dates are not available for all data and, more importantly, because it could not be ascertained whether correction factors had already been applied. To make matters worse, some organic carbon values, recorded as using the uncorrected Walkley–Black method, were found to be greater than those that had been apparently corrected for incomplete recovery. In the end, it was decided that no correction factor would be used. While this probably resulted in underestimation of organic carbon, most data were from the last 30 years and this ensured the effect was small compared to correcting values already adjusted.

Although many data are often compiled, it is common for only a small proportion to be of value in a synthesis study. For example, Henderson et al. (2001) had access to 151 810 horizons with pH measurements. Around one-third were from A horizons, giving about 50 000 possible records for estimating ‘topsoil’ pH. Only determinations using methods 4A1, 4B1 and 4B2 could be compared – just over 70% of the data – reducing the number to 35 000. After removal of records with ambiguous designations for horizons or some other inconsistency, the total number of records available for estimating topsoil pH was 25 915. The situation is worse for other chemical and physical properties. For example, preparation of an improved continental map of soil carbon was hindered by the paucity of data on organic carbon, bulk density and coarse fragments – the latter two being necessary for calculation of carbon on a volumetric basis.

Framework for data

To meet the objective of the synthesis study, it is usually necessary to develop a framework to handle the various sources of data so that the data are presented in a uniform way. Designing and negotiating this framework can be time-consuming and difficult, but it is essential for a successful study. McKenzie et al. (2005) is a recent example and you should use its structure as a checklist for new studies.

Point data

The various databases of point data are likely to have different structures and standards. Before use, they need to be transformed into a common database structure. The recommended structure is the SITES transfer standard format (ACLEP 1997). Locations of all points require a common datum and projection (i.e. GDA94, see *Chapter 16*).

Map data

Differences in map legends, mismatched line work at the edges of map sheets and variations in scale are major problems in establishing a consistent map across a region. The problems are exacerbated by the variety of survey methods employed across Australia (Beckett and Bie 1978; Gibbons 1983; McKenzie 1991). Most have been based on some form of integrated or soil–landscape survey (Christian and Stewart 1968; Mabbutt 1968; Northcote 1984) at medium to reconnaissance scales (1:50 000–1:250 000). However, Speight (1988) notes that the wide variation in mapping practice among different Australian survey organisations is largely a matter of level of classification or precision, rather than a difference in the conceptual units that surveyors recognise and describe. As a result, most map units can be translated into the hierarchy of land-unit types in Table 3.2 developed for the Australian Soil Resource Information System.

Most synthesis studies provide estimates of soil properties for individual land units that are then used as inputs to simulation models. Pedotransfer functions (see *Chapter 22*) are nearly always employed for this purpose (e.g. Carlile et al. 2001; Henderson et al. 2001, 2005). Class pedotransfer functions for physical properties of soils are available for the

Table 26.3 Comparison of laboratory methods used for determination of pH for records in the Australian Soil Resource Information System (ASRIS) database

No. of horizons with laboratory measurement	Method code ^A	Method description
72 152	4A1	pH of 1:5 soil/water suspension
231	4A_C_1	pH of soil – pH of 1:1 soil/water suspension
3664	4A_C_2.5	pH of soil – pH of 1:2.5 soil/water suspension
38 268	4B1	pH of 1:5 soil/0.01M calcium chloride extract – direct
3747	4B2	pH of 1:5 soil/0.01M calcium chloride extract – following Method 4A1
505	4B_C_2.5	pH of soil – pH of 1:2.5 Soil/0.1M CaCl ₂ suspension
892	4C1	pH of 1:5 soil/1M potassium chloride extract – direct
231	4C_C_1	pH of 1:1 soil/1M potassium chloride suspension
284	4E1	pH of hydrogen peroxide extract
237	4G1	Total potential acidity
31 599	4_NR	pH of soil – not recorded

^A From Rayment and Higginson (1992).

Principal Profile Forms defined by Northcote (1979) (McKenzie et al. 2000; Smith 2002), but not for other classifications. Heed the caveats supplied with these publications and only use pedotransfer functions as a last resort (see also guidelines in *Chapters 21* and *24*, and investigate the uncertainty of predictions). A starting point is the procedure for estimating uncertainty in the current version of the Australian Soil Resource Information System.

Analysis

The previous stages are all concerned with preparing data for analysis. A common objective is to predict attributes at all points in a region.

Models from maps

Beckett and Bie (1978) recognised that users of maps and reports often find that the original soil surveyor is the most useful source of information, superior to anything on paper. The map and report are less than efficient communication tools and this is of critical importance to synthesis studies. In an attempt to capture this extra knowledge, strategies have been devised to extract more information out of existing surveys. Attention has focused on reformulating the mental models used by the surveyor (Hudson 1992; Hewitt 1993; Webb 1994). Bui (2004) provides the theoretical background and a formal logic for representing the knowledge acquired by surveyors.

The strategy for remapping soils in the Murray–Darling Basin is shown in Figure 26.1; the aim here was to make the most out of existing maps with a minimum of new fieldwork (Bui and Moran 2003). Existing soil maps were used as training areas to develop rules to predict soil classes defined by Northcote’s (1979) system. The rules employed environmental variables as predictors, and different maps produced different sets of rules. The existing maps were also

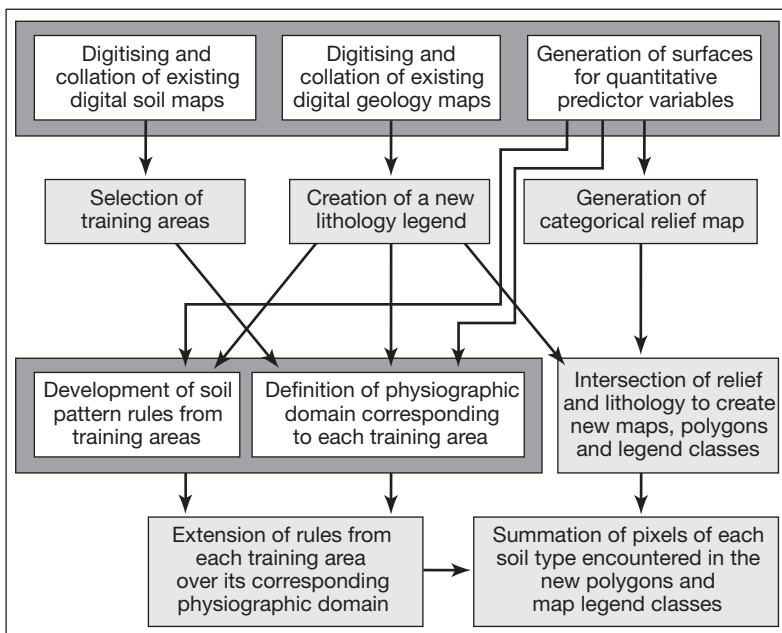


Figure 26.1 Flow diagram of the implementation of the strategy for remapping the Murray–Darling Basin.

used to define the domain over which these rules could be applied. The derived rules were then implemented using the Basin-wide environmental variables to predict soil classes over gaps in the existing soil coverage. Conceptually, the approach is analogous to that advocated by Favrot (1989) and Lagacherie et al. (1995) but at reconnaissance scale and using existing maps as reference areas (see *Chapter 18*). The approach is similar to digital soil mapping with environmental correlation and relies on the following assumptions:

- soil distribution reflects the long-term interactions between terrain variables, geology and vegetation
- terrain attributes derived from a digital elevation model can represent some factors of soil formation
- the existing soil maps have captured soil–landscape interactions in the mapped areas.

Bui and Moran (2001, 2003) describe the procedure for the study of the Murray–Darling Basin, while Henderson et al. (2005) describe methods for estimating soil properties across intensively used land in Australia. The data sets in these studies are large and the analyses are complex. Make sure you understand the procedures applied in these pioneering studies and pay attention to the following problems.

Ensuring surveys provide maximum benefit

Large synthesis studies such as those for the Murray–Darling Basin and ASRIS are ultimate tests for the quality of survey data. They can take place many years after the original surveys when the surveyors are no longer available to assist with interpretation. If the survey has been inadequately reported or the data inadequately documented and managed, the usefulness of the data will be compromised. Make sure the data you record are free from the problems listed below, and use the list during the planning phase of a synthesis study to set realistic objectives. The major obstacles to synthesis studies in our experience are:

- inadequate data licensing agreements
- existing maps are not digitised
- maps have no reported datum or projection
- the source data contain allocations to inconsistent classification systems
- there is restricted availability of environmental data relating to terrain, lithology, land use and vegetation
- data are presented in an abbreviated tabular form without a proper description of map units (e.g. no information on the proportion of a land unit occupied by different soil profile classes)
- sampling for soil profiles is biased
- quality assurance in the original surveys is poor and the source data have typographical errors, unstated units of measurement and unreliable positional accuracy
- sensible stratification and appropriate application of rules for spatial prediction is restricted by a poor understanding of geomorphology and pedology for the region.

Most effort in synthesis studies is spent preparing data. Do not underestimate how long this can take. Technology and the passage of time will improve the diversity, coverage and resolution of the spatial data that can be used as predictor variables. This will provide new possibilities for making use of existing data in synthesis studies. Nevertheless, the products of those models depend on the quality of the survey data used as input and the associated metadata. Explain to users how the products can be used and be clear about their limitations.

The central place of synthesis studies

Internet access to soil data, and spatial data more generally, is increasing quickly. This results from several factors, including:

- introduction and wide acceptance of standards for spatial data (e.g. Open Geospatial Consortium) leading to data becoming available through Web Map Services, Web Feature Services, Web Coverage Services and Web Processing Services (Open Geospatial Consortium 2006)
- general availability of open source and proprietary software for Web Map Services
- more enlightened attitudes to the sharing of data
- new software for visualisation, for example NASA's World Wind (NASA 2006) and Google Earth (Google 2006).

These developments are generating demand for consistent soil information at fine resolution and across large extents. This information has to be intelligible to those outside the soil science community and it must be useful for assessing how land can best be used. This is an enormous challenge and it means that synthesis studies are now *the* central activity in land resource assessment. It is essential that surveys be undertaken in a way that adds to the broader view at the regional and continental scale, otherwise the benefits of using the data over and over again will never accrue.

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Plate 1

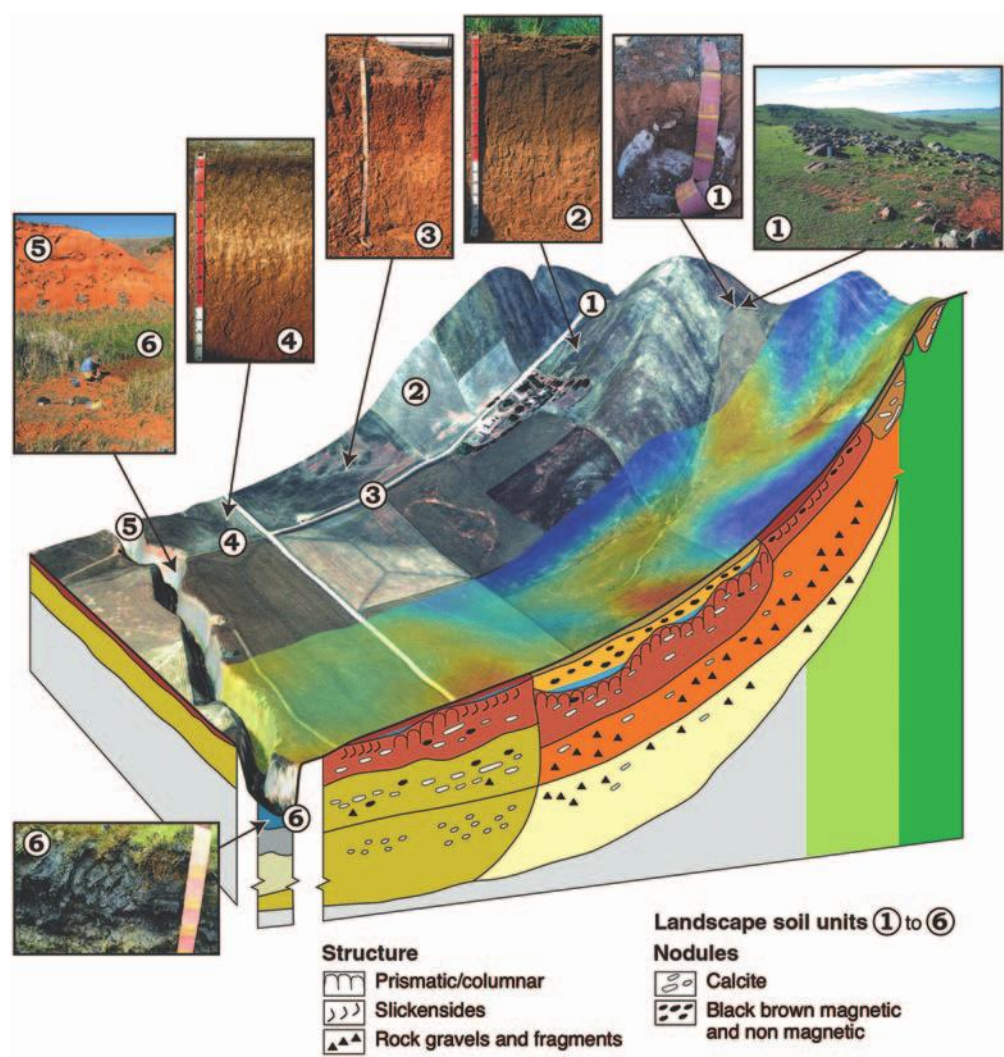


Figure 2.1 The landscape continuum (after Thomas et al. 2005).

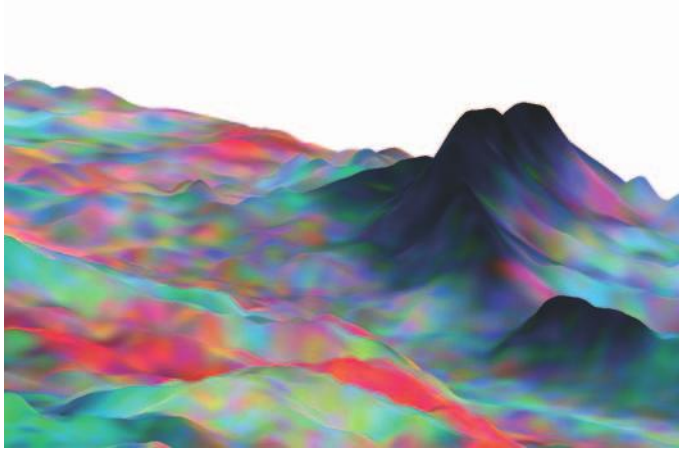
Plate 2

Figure 13.4 Landscape perspective with gamma-ray image draped on an elevation model over part of the Mount Lofty ranges in South Australia. Combining gamma-ray spectrometric images with digital elevation models (DEM) as perspective views enables the visualisation of relationships between gamma-ray responses and landform (e.g. erosional and depositional landscapes).

Plate 3

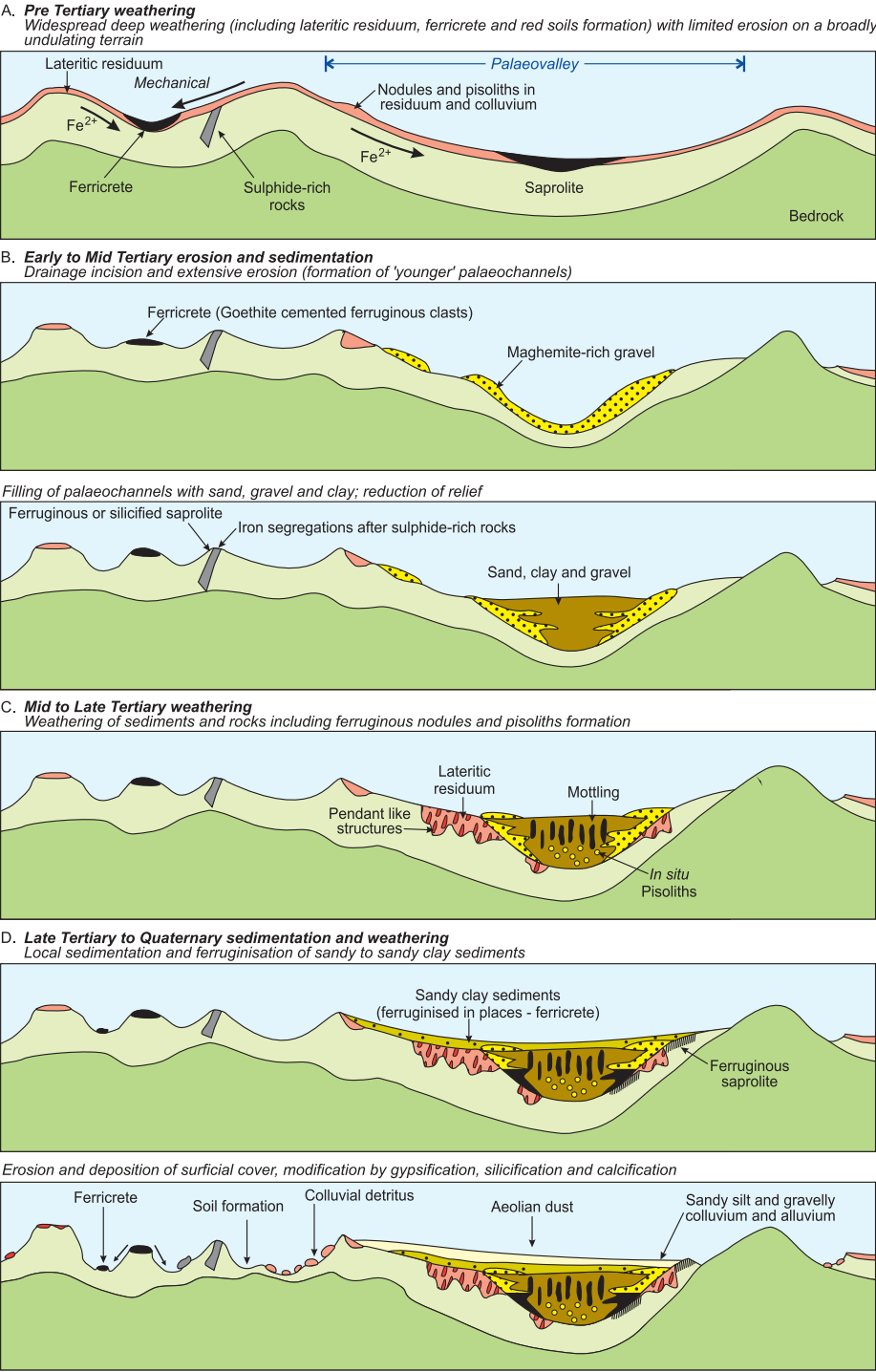


Figure 32.3 Interpreted regolith-landscape model showing general regolith-forming processes characteristic for part of the inland Yilgarn Craton (Anand and Paine 2002).

Plate 4

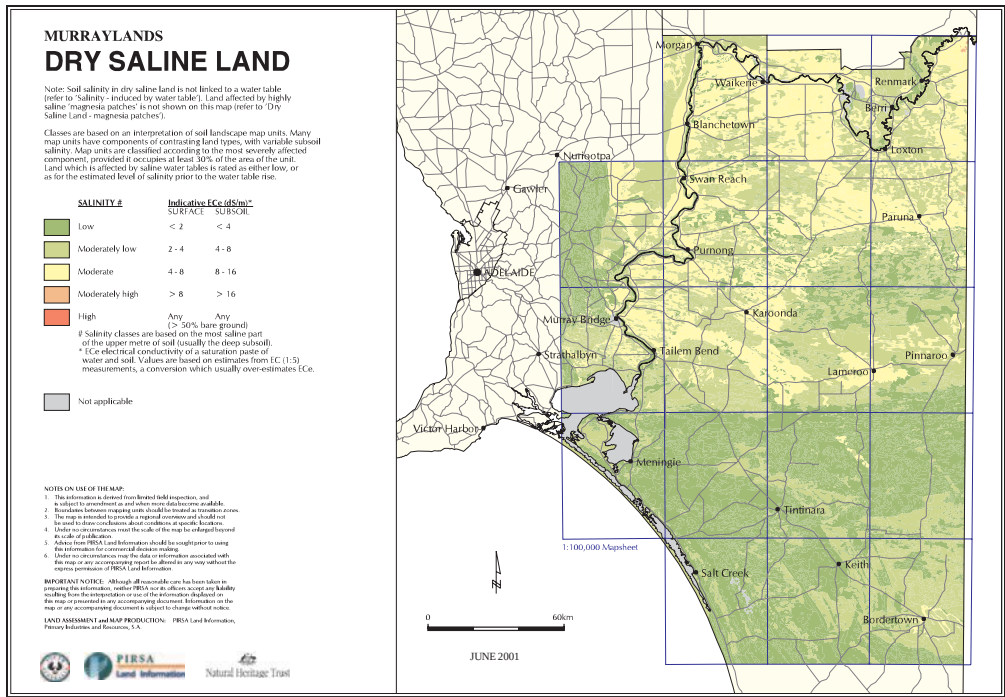


Figure 32.4 (a) Extract of maps from the South Australian Regional Land Information Series published PDF documents on CDs.

Plate 5

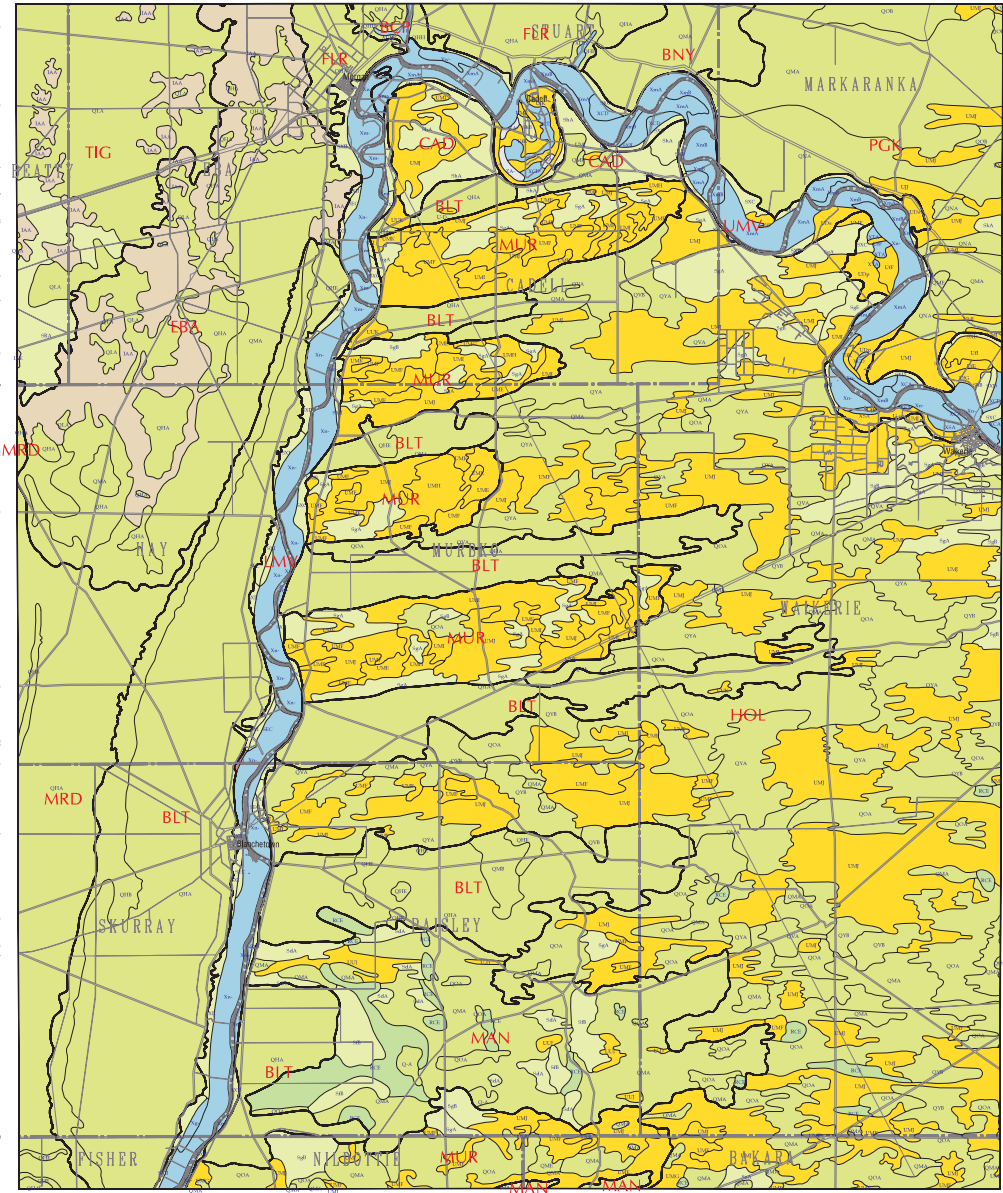
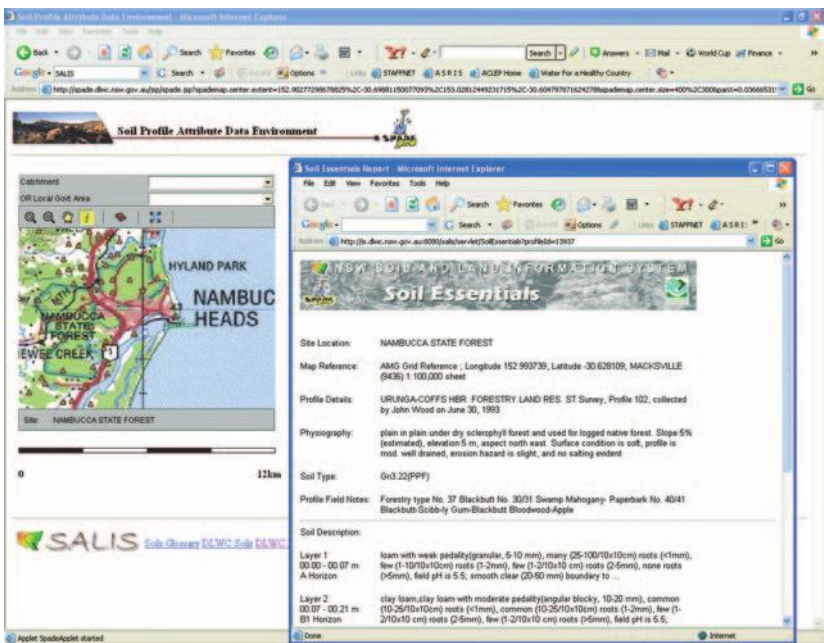


Figure 32.4 (b) Detailed maps of soil types available as PDF documents from the Regional Land Information Series for South Australia.

Plate 6

(a)



(b)

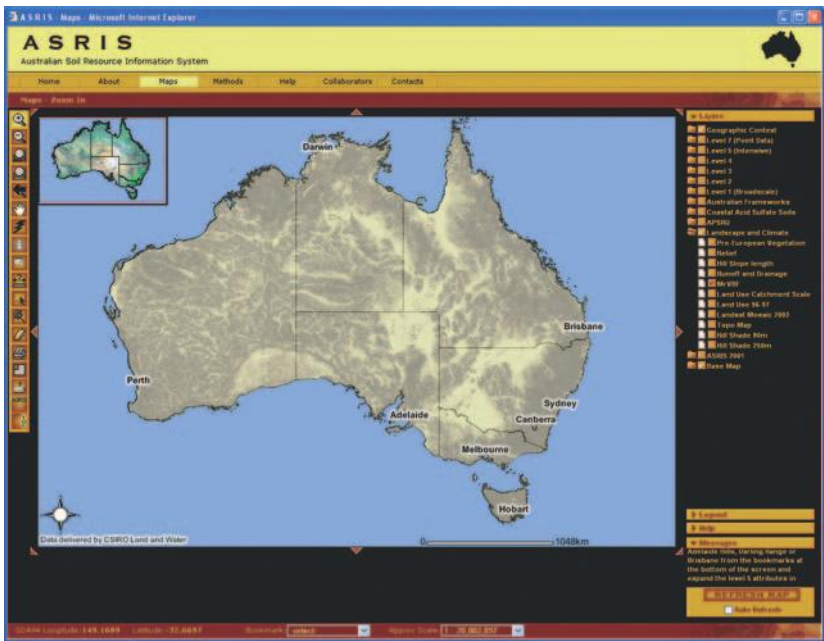
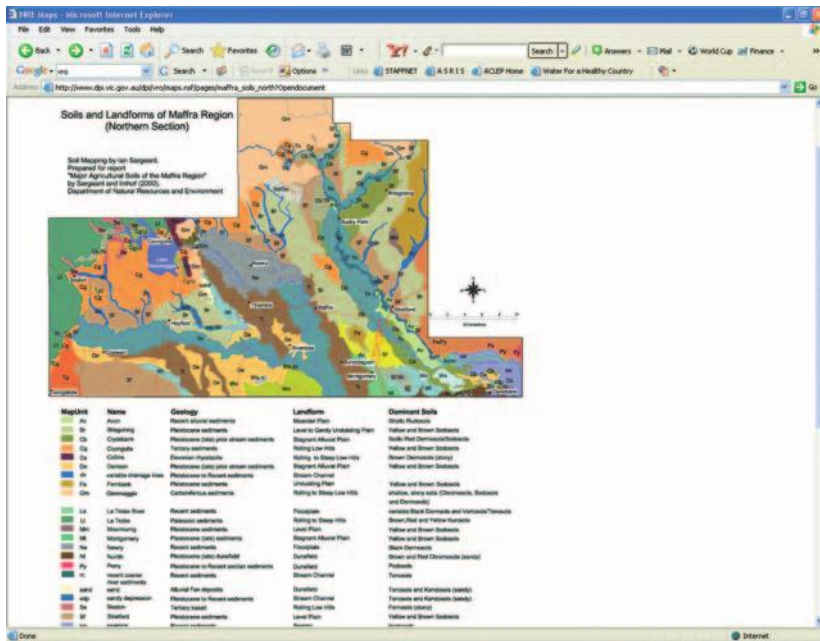


Figure 32.5 On-line access to soil information is possible through a variety of systems including (a) SALIS and SPADE (NSW Department of Natural Resources 2006) and (b) ASRIS (2006).

Plate 7

(a)



(b)

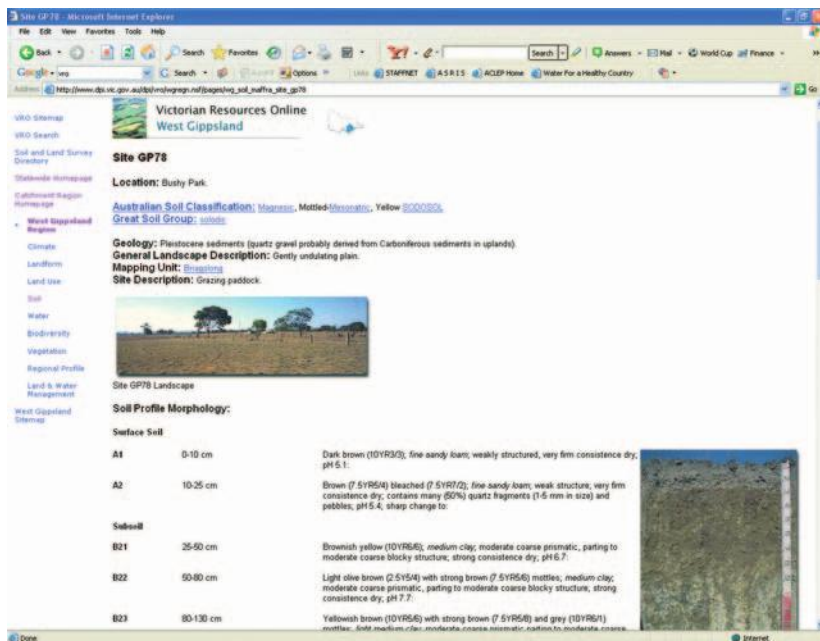


Figure 32.6 Survey reports available from Victorian Resources Online (VRO 2006) with active links to glossaries and maps.

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Part 5

Land evaluation

Land evaluation is the process of estimating the potential of land for alternative kinds of land use so that the consequences of change can be predicted. Procedures are presented for estimating the suitability of land for various land uses through to formulating precise strategies for land management (e.g. irrigation, horticulture, land use planning). The link between survey and monitoring is introduced. Legal and planning issues are then reviewed before concluding with a guide to the all-pervasive task of communication.

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Conventional land evaluation

D van Gool, DJ Maschmedt, NJ McKenzie

Introduction

Technical outputs from surveys require interpretation, or land evaluation, to make the information more useful. Land evaluation is ‘the process of estimating the potential of land for alternative kinds of land use so that the consequences of change can be predicted’ (Dent and Young 1981). Land evaluation is distinct from the collection of primary survey data and, over time, many interpretations will be made as land use requirements change and new options for land use emerge.

Land evaluation requires biophysical, social and economic information. The focus in this chapter is on biophysical information. Surveyors are rarely asked to solve land allocation problems by devising maps of the most suitable land uses for a region (see *Chapter 1*). Instead, they are more likely to be members of interdisciplinary teams that advise on optimal land use allocation and land management. This advisory role is increasing as data on land resources become more widely available in digital form to a broad range of users, many of whom have access to sophisticated methods for data analysis (e.g. simulation modelling).

This chapter describes how to use conventional methods for land evaluation. These methods depend heavily on expert knowledge. The methods evolved over several decades, arguably reaching a climax with publication of the FAO Framework for Land Evaluation (FAO 1976). Some see this as marking the end of the era for conventional land evaluation (e.g. van Diepen et al. 1991), but we (the authors) interpret it as just another step in the development of better methods. Quantitative land evaluation (see *Chapter 28*) can be viewed as the natural successor for the conventional methods outlined in this chapter; however, the situation is not that simple and both approaches have strengths and weaknesses. Furthermore, it is an oversimplification to refer to either conventional or quantitative approaches – in reality, a spectrum exists with different degrees of quantification.

Approach and purpose

Approaches to land evaluation were outlined in Part 1 (see *Chapter 1*). There are many methods and one classification is presented in Table 27.1. McRae and Burnham (1981), Dent and Young (1981), van de Graaff (1988), Bouma (1989a,b), Rossiter (1996), and Shields et al. (1996) provide useful reviews. The critique of conventional methods by van Diepen et al. (1991) is valuable.

A basic distinction is made here between static and dynamic methods of assessment. Static methods provide ratings of either:

Table 27.1 A classification of methods for land evaluation (based on Rossiter 1996)

Assessment applied	Dynamics	Output	Description
Independently to individual land units	Static land attributes	Maps of static land suitability classes	Conventional FAO-style land evaluation
	Dynamic	Maps of static land suitability	Simulation models used to identify suitability
	Dynamic	Dynamic	
Independently to individual land unit tracts but location is important	No interactions between land unit tracts		
	Static interactions between tracts		
	Dynamic interactions between tracts		
Multi-area suitability assessment and land allocation	Static land attributes, no interactions between tracts		
	Static land attributes, interactions between tracts		
	Dynamic land attributes and interactions between tracts		Simulation modelling in time and space to identify optimal land performance

- land performance (e.g. potential yield of crops and pastures, water supply)
- required inputs for management (e.g. land conservation works necessary for sustainable use), or
- hazard of use (e.g. erosion, acidification; Gibbons 1976).

Dynamic methods (see *Chapter 28*) usually involve simulation modelling in some way to rate land performance. These methods capture, to varying degrees, interactions between land attributes, land use and landscape processes.

The static methods of land evaluation considered in this chapter usually depend on rules, and the results are nearly always presented as suitability classes. Rule-based methods have dominated land evaluation for several decades and they continue to be useful.

The classification in Table 27.1 also discriminates between methods according to whether land units are considered independently of their neighbouring units. This distinction is particularly significant when considering processes such as salinisation or sediment delivery to streams. In the former instance, the distance between recharge and discharge zones might range from a few hundred metres to tens of kilometres.

Landscape classifications such as groundwater flow systems (Coram et al. 2000) attempt to capture the scale of spatially related processes using a static representation. Rule-based systems can be used to rate land performance in these cases, but the complexity of interactions and nature of the processes favour analysis with simulation models of some form – these do not need to be complex.

Another discriminator in Table 27.1 is the number of land units considered at each step during the assessment process, and whether an attempt has been made to identify a preferred

land use. This may be at the local scale (e.g. identifying the optimal layout of paddocks for cropping and grazing, specifying preferred use of management zones within a forest or national park). At a more general scale, an example is in urban planning where nominated zones are needed for different forms of land use (e.g. housing, utilities, green belts, floodways). The analysis may seek to explore trade-offs between competing objectives (e.g. maintain biodiversity, maximise agricultural production, control salinity, secure water resources). This style of analysis requires a very strong interdisciplinary base and a high level of interaction with stakeholders. The methods for these types of analyses are beyond the scope of these *Guidelines* – see Costanza and Voinov (2004) for one approach.

The remainder of this chapter considers static methods for land evaluation and here the emphasis is on rule-based systems. Methods involving indices derived from multiplicative or additive procedures have been proposed but rarely used in routine assessment in Australia. McRae and Burnham (1981) and Rossiter (1996) review these. Rule-based methods are effective because they usually identify the most limiting factor(s) that affect the performance of a land use. The style of rule-based system varies with the scale of application.

Synoptic assessments

Land evaluation at a synoptic level (global, continental, regional) is essential for placing more detailed assessments in context. Results from synoptic studies can identify hazards of land degradation and estimate productivity in a general way. This can form the basis for investing limited resources and commissioning further assessments that eventually lead to action on the ground.

Rule-based assessments at a synoptic scale are strongly constrained by the availability of data. Until recently, the *Atlas of Australian Soils* was the primary data source for soils at the continental level. Most assessments involved interpretations of Principal Profile Forms and thereby, for example, identified saline and sodic soils (Northcote and Skene 1972) or assessed the suitability for agriculture (Northcote et al. 1975; Dunlop et al. 2000). Publication of class pedotransfer functions to accompany the *Atlas* increased its use (often for simulation modelling) but at the same time highlighted deficiencies in the primary data set (McKenzie et al. 2000). Synoptic assessments in recent years have relied increasingly on simulation models (e.g. NLWRA 2001, see *Chapter 28*).

Regional planning

Demand for land resource information at the regional scale has waxed and waned. During the 1970s, many studies were undertaken to address land conservation needs. Land evaluation focused on identifying the capability and suitability of land for various forms of agriculture, forestry and conservation.

Responsibility for managing natural resources in Australia has been decentralised in recent years, partly resulting from the success of the Landcare movement, and more than 50 regional authorities for catchment management have been established. There has been an associated stimulation of demand for land evaluation at the local and regional level. Authorities are:

- setting targets for water quality and land management
- developing strategies for conservation and revegetation (primarily to improve water quality, minimise salinity, and restore biodiversity)
- promoting sustainable practices of land management.

Survey groups are now being asked to supply more than maps of land suitability or degradation hazards. For example, baselines are needed for soil carbon, pH and a range of other indicators of soil and land condition; predictions are needed for surface hydrology and deep

drainage across a broad range of soil types and cropping systems; and estimates are needed of the risk of sediment and nutrient transport to waterways. Some of these new demands are complex to solve, both technically and institutionally. Static methods provide answers in some circumstances, but dynamic methods are required in others (see *Chapters 28 and 30*).

Local planning

Static methods of land evaluation are most useful for local land use planning and management (e.g. Kininmonth 2003). Clients are local government and regulatory authorities such as environmental protection agencies. Since local authorities make the key decisions about zoning and use of individual parcels of land, clear-cut rules are needed to identify the suitability of land for a range of purposes and to protect areas prone to degradation. Attention is directed to mapping and assessing issues such as:

- strategically important agricultural areas
- areas suitable for urban and periurban development
- distribution of acid-sulfate soils
- eutrophication and toxic algal blooms
- salinity
- erosion-prone land
- hazards to infrastructure caused by shrink–swell
- risk of sediment export (e.g. Marsh 2002)
- suitability of land for effluent disposal (e.g. Bond 2002) or land-fill.

Land evaluation for local planning becomes important when requirements are specified in legislation and supporting regulation. For example, the legislative requirements to protect prime agricultural land or proscribe development on acid-sulfate soils demands an explicit system for assessment that can survive legal challenge. Rule-based systems are well suited to these situations and examples are given below.

Property planning and management

Formal rule-based systems for land evaluation to support property planning and management tend to be restricted to public lands and to intensive developments for plantation forestry, irrigated agriculture, horticulture and viticulture (see *Chapter 29*). Significant efforts are devoted to property planning in agricultural areas and the main focus is on land degradation and the promotion of long-term sustainability and profitability. Several systems exist for rating the suitability of agricultural land, particularly with respect to the management needs of different soil and cropping systems; however, many assessment systems for property planning and management are locally based and draw heavily on the expertise of local experts (e.g. agronomists, land conservation officers, farm foresters, Landcare officers). Examples of rule-based systems to support property planning and management include soil management guidelines (McKenzie 1998) and manuals for land management (Thwaites and Macnish 1991; Thwaites 1992).

Precision farming

Precision farming, whether for cropping, grazing, horticulture, viticulture or forestry, is a particular form of property planning and management. It differs from the examples in the previous section through its emphasis on sophisticated technology for mapping and, to a lesser extent, interpretation. Interpretations of soil and yield data are often expressed in economic terms (e.g. gross margins) and physical land evaluation focuses on management

inputs and resulting crop yield. Useful overviews are provided by Robert (2002) and Stafford and Werner (2003).

Terminology and principles

Most rule-based systems assign ratings to land units according to the most limiting factor that affects a specific land use. The terminology and principles are well established, resulting largely from the influence of the *FAO Framework for Land Evaluation* (FAO 1976). This milestone in land evaluation developed from international consultations organised by the United Nations Food and Agriculture Organization (FAO) during the early 1970s. Many of the ideas were introduced to Australia by Gibbons (1976) and then adapted in state systems (e.g. Rowe et al. 1981). Some States developed similar systems without formally adopting the *FAO Framework* (e.g. Wells and King 1989; Land Resources Branch Staff 1990) – this has resulted in some confusion over terminology (e.g. see *Land suitability versus land capability*).

Legacy of the FAO Framework

The *FAO Framework* does not prescribe methods but is instead a set of principles and concepts, together with a terminology, on the basis of which local, regional or national systems can be constructed. The *Framework* is also useful to some extent for quantitative methods (e.g. Bouma 1989b). A good summary of the *FAO Framework* is provided by Dent and Young (1981). Also refer to the guidelines for dryland agriculture (FAO 1983), forestry (FAO 1984), irrigated agriculture (FAO 1985), steepplands (Siderius 1986) and extensive grazing (FAO 1991). This chapter aims not to repeat operational details on how to implement an FAO-style assessment – refer to the aforementioned publications for this. Instead the principles and methodological issues relevant to the Australian setting are outlined.

The apparently simple terminology of the *FAO Framework* is useful, and it leads to better communication between many workers. However, critics (e.g. van Diepen et al. 1991) argue to the contrary. Deficiencies are considered (see *Developments*). Here the terminology summarised by Rossiter (1996) is used.

- ▶ A *land characteristic* is a simple attribute of land that can be measured or estimated in routine survey (e.g. pH, slope, surface reflectance).
- ▶ In contrast, a *land quality* is a complex attribute of land that acts in a manner distinct from the actions of other land qualities in its influence on the suitability of land for a specific use (e.g. moisture availability, erosion hazard). It is the ability of the land to fulfil the specific requirements for a *land utilisation type* (see *Land utilisation type* below). It cannot usually be measured or estimated in routine survey, and so needs to be inferred from a set of diagnostic land characteristics. Land qualities take account of interactions between relevant land characteristics. Bouma et al. (1986) have developed the terminology further to make distinctions between dynamic and static characteristics, and between those measured on continuous and nominal scales (e.g. soil profile class). Table 27.2 lists land qualities relevant to dryland agriculture.
- ▶ A *major kind of land use* is a land use considered at a broad or reconnaissance level (e.g. dryland agriculture, forestry, urban or nature conservation).
- ▶ A *land utilisation type* is a land use described in a greater degree of detail than that of a major kind of land use. It is a system of land use with explicit management methods in a defined technical and socioeconomic setting, and with a specific duration or planning horizon. The description may be in terms of produce, capital and labour requirements, assumed technology, dimensions of minimum management units, biophysical requirements and tenure. Preparing descriptions of land utilisation types prior to field survey guides data collection, mapping and analysis.

Table 27.2 Land qualities relevant to dryland agriculture (after Dent and Young 1981)

No.	Land quality	Subdivision	Potential land characteristics to measure or estimate the quality
1	Radiation regime	Radiation requirements Daylength	Mean daily sunshine hours in growing season Day length at floral initiation
2	Temperature regime		Mean temperature in growing season; coldest and/or hottest months of growing season
3	Growing period		Calculated growing period (days)
4	Air humidity as affecting growth		Mean relative humidity of least humid month in growing season
5	Conditions for ripening		Period of successive days rainless and with specified minimum sunshine hours and/or temperature days
6	Conditions affecting post-harvest operations		Varies with crop (e.g. humidity of month following harvest)
7	Conditions affecting timing of production		Varies with crop and region (e.g. earliest date specified soil temperature or water content is reached)
8	Climatic hazards	Frost	Frequency of damaging frosts in growing season
		Storm	Frequency of damaging storms in growing season
9	Water availability	Total	Relative evaporation deficit, total for growing period, no. of humid months, rainfall greater than potential evaporation; length of dry season, rainfall less than specified amount, etc.
		Critical periods	Relative evaporation deficit, critical period for crop
		Drought hazard	Probability of rainfall less than specified amount, for growing season, year, or critical period
10	Drainage (oxygen availability to roots)		Soil drainage class, depth to soil mottling, depth to water table at specified period, vegetation indicators
11	Flood hazard		Period of inundation during growing season, frequency of occurrence of damaging floods
12	Nutrient availability		Nutrient levels by topsoil analysis (N, P, K, other); indicators of nutrient availability and/or renewability (pH, ratio $\text{Fe}_2\text{O}_3/\text{clay}$, weatherable minerals percentage, total P or K); fertility capability classification, presence of condition modifiers a, h, i, x, k
13	Nutrient retention		Cation exchange capacity, total exchangeable bases, texture class
14	Rooting conditions		Soil effective depth, degree of limitation to root penetration based on texture, structure, consistence, bulk density

No.	Land quality	Subdivision	Potential land characteristics to measure or estimate the quality
15	Workability		Degree of limitation to workability based on topsoil texture, structure, consistence, topsoil texture class
16	Conditions affecting germination or establishment		Varies with crop and area (e.g. soil conditions for seedbeds)
17	Excess of salts	Salinity, sodium alkalinity	Electrical conductivity of saturation extract, total soluble salts
			Exchangeable sodium percentage, sodium absorption ratio
18	Toxicities	Al, CaCO_3 / CaSO_4 , Mn, acid sulfate	pH, Al saturation; % CaCO_3 / CaSO_4 in root zone, depth to calcrete, gypsum; presence of/depth to actual or potential acid sulfate horizon
19	Physical degradation hazard		Index of rainfall erosivity, index of crusting, observed signs of crusting
20	Erosion hazard	Water erosion, wind erosion	Potential soil loss as calculated by the universal soil loss equation, surface cover, slope $\times$ texture
			Texture, surface cover
21	Pests and diseases		Properties of climate or soil affecting incidence (e.g. humidity)
22	Land preparation		Varies with crop and region
23	Potential for mechanisation		Degree of limitation to mechanisation (e.g. slope, wetness)
24	Access within production unit		Terrain limitations including slope, relative relief, presence of gullies, swamps
25	Size of potential management units		Minimum size of acceptable units
26	Location		Distance from processing plants or ports, distance from sealed roads

- A *land use requirement* is a condition of the land necessary for successful and sustained implementation of a specific land utilisation type. The latter may be defined by a set of land use requirements.
- *Land suitability* is the fitness of a given area for a land utilisation type, or the degree to which it satisfies the land user. It is commonly expressed as a set of discrete classes that are usually numbered from Class 1 (completely suited) upwards to some maximum (often Class 5), meaning completely unsuited (Table 27.3). The FAO *Framework* specifies a system of suitability orders, classes, subclasses and units (Table 27.3).

The main activities in an FAO-style assessment are shown in Figure 27.1. To implement the method, we recommend the following.

- Describe all potential land uses and management systems for the study area (i.e. the major kinds of land use or the land utilisation types) prior to the survey or data collection phase.
- Identify the land use requirements for each land use. Express these requirements as land characteristics and qualities, and prepare rating schemes for assessing land suitability.

Table 27.3 Scheme for classifying land suitability according to the FAO *Framework*

Order	Class	Description
S Suitable	S1 Highly suitable	Land having no significant limitations to sustained application of a given use, or only minor limitations that will not significantly reduce productivity or benefits and will not raise inputs above an acceptable level
	S2 Moderately suitable	Land having limitations which in aggregate are moderately severe for sustained application of a given use; the limitations will reduce productivity or benefits and increase required inputs to the extent that the overall advantage to be gained from the use, although still attractive, will be appreciably inferior to that expected on Class S1 land
	S3 Marginally suitable	Land having limitations which in aggregate are severe for sustained application of a given use and will reduce productivity or benefits, or increase required inputs, that this expenditure will be only marginally justified
N Not suitable	N1	Land having limitations which may be surmountable in time but which cannot be corrected with existing knowledge at currently acceptable cost; the limitations are so severe as to preclude successful sustained use of the land in the given manner
	N2	Land having limitations which appear so severe as to preclude any possibilities of successful sustained use of the land in the given manner

Subclasses can be denoted with subscripts for the limiting land quality (e.g. S3i is marginally suitable because of waterlogging – see Table 27.6 for subscripts). One can make further divisions into suitability units. These are divisions of suitability subclasses (designated by numbers within subclasses such as S3i-2) which are meant to be managed similarly. These have different management requirements but the same degree of limitation and the same general kind of limitation (because they are divisions of subclasses) (e.g. ‘moderate’ fertility limitations, but one management unit may require extra K and another extra P) (Rossiter 1994).

- ▶ Map the distribution of land use requirements across the study area.
- ▶ Depending on the scale of the study, evaluate the suitability of each land unit for either major kinds of land use or land utilisation types.

Each step is considered in more detail after clarifying the difference between the FAO definition of land suitability and the original definition of land capability by the United States Department of Agriculture (USDA).

Land suitability versus land capability

The FAO *Framework* was a substantial improvement over previous systems for land evaluation and, in particular, over the technique for land capability assessment for farm planning developed by the Soil Conservation Service of the USDA (Klingbiel and Montgomery 1961). The prime aim of the USDA system was to assess the degree of limitation to use imposed by land characteristics that were considered virtually permanent. The system was intended to interpret information collected during detailed (1:20 000) county soil surveys in a way that could be readily understood by farmers, planners and other users. Land units were allocated to classes ranging from I to VIII.

The USDA capability classification focuses on agriculture and does not provide an explicit basis for trade-offs between competing land uses. It carries an implicit priority of uses: cultivation is most important, followed by grazing, with recreation and wildlife conservation at the lowest level. This restricts its value for resolving most problems in managing natural resources.

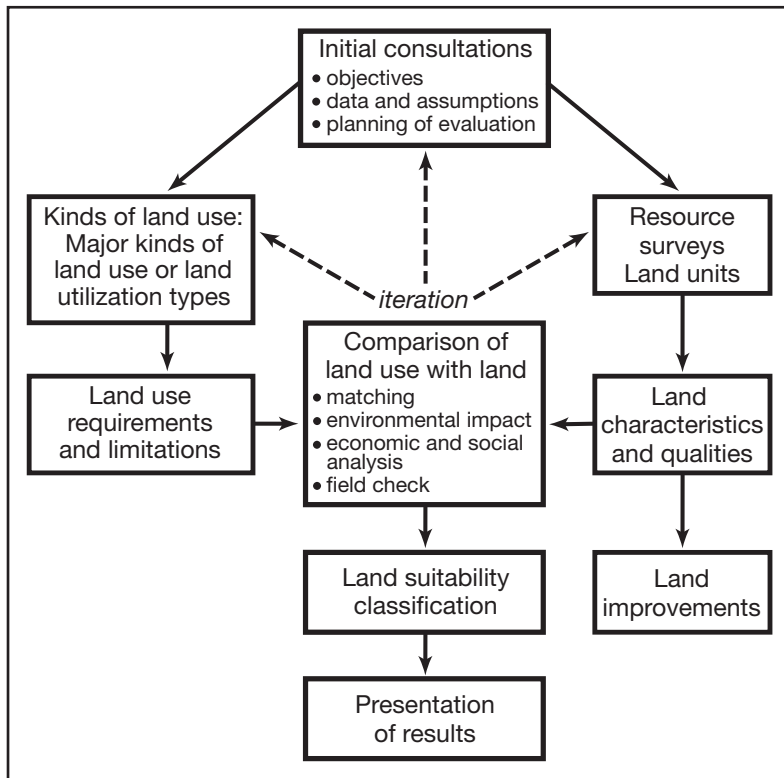


Figure 27.1 Activities involved in an FAO-style assessment (Dent and Young 1981).

The system emphasises the risk of erosion, not productivity. It also assumes a certain level of technology and management inputs. Although these features simplify the system, they also limit its utility.

Beek (1981) concluded that the USDA system, of which there are several Australian derivatives (e.g. Rosser et al. 1974; Hannam and Hicks 1980), is useful for broad planning purposes at regional and national levels, provided that the underlying assumptions about management and land use reflect the true situation. For more detailed planning, the classes are of little significance and need to be replaced by separate evaluations for precisely defined land utilisation types. A similar conclusion was reached by several Australian agencies (e.g. van der Graaff 1988; Land Resources Branch Staff 1990).

The FAO (1976, 1983) concept of *land suitability* differs from the USDA notion of *land capability* in several ways. FAO (1976, 1983) define land suitability as the fitness of a given type of land for a specified kind of land use. The difference with land capability assessment is its prior specification of the precise form of land use (via the land utilisation type description) and the matching of the land use requirements with the attributes of the land. Separate schemes for evaluating suitability are devised for each land utilisation type. Unfortunately, the term land capability is used in several ways by Australian agencies (van der Graaff 1988). Logically, only use the term in relation to assessments made with land capability classification systems derived directly from the USDA scheme. Use the term land suitability wherever evaluations are made for specified land uses.

Implementing an FAO-style assessment

Land uses and their requirements

The process of preparing descriptions of land use varies from survey to survey and is a substantial task. The Terms of Reference provide the starting point and usually define which uses to consider and their degree of detail. You will need a good understanding of land management to prepare descriptions of land utilisation types and a checklist relevant to irrigated agriculture is provided (Table 27.4). Consult widely and seek advice from relevant experts including agronomists, foresters, farmers, land managers, economists, engineers, planners, social scientists and other relevant experts in the region. Seek feedback on draft descriptions.

Table 27.4 Checklist of headings for preparing a description of land utilisation types for irrigated agriculture (after FAO 1985)

	Heading	Description
1	Cropping system	Single, multiple or compound land utilisation types. Crops grown, cultivars, cropping calendar, cropping intensity. Perennial cropping systems, cultivation factor, cropping index
2	Markets	Domestic or export, or both
3	Water supply	Seasonal supply and quality
4	Irrigation method	Gravity or lift, run-of-river or storage releases, surface, overhead, drip, etc.
5	Capital intensity	Value of capital investment and recurring costs per ha
6	Labour intensity	Family and hired labour, person-months per ha, seasonal peak periods, festivities and holidays
7	Technical skills and attitudes	Experience, response to innovation and change, literacy
8	Power	Extent of human, animal and tractor power impact on land preparation, harvesting, etc.
9	Mechanisation and farm operations	Which operations are mechanised or partly mechanised.
10	Size and shape of farms	Farm size, fragmentation of holdings, rainfed and irrigated areas
11	Land tenure	Freehold: family farm, corporately owned property
		Tenancy: rental, share cropping
		Communal ownership: cooperative (collective) farming, commons with rights to cultivate, etc.
		Public ownership: leasehold land
12	Water rights	Public or private ownership, tradable or otherwise
13	Infrastructure	Assumptions about processing facilities, storage depots, markets, access to farm inputs. Roads, housing, schools, medical facilities, electricity, domestic water supplies. Research and extension services and facilities
14	Irrigation infrastructure	Assumptions about irrigation and drainage infrastructure and access to irrigated land
15	Material inputs	Prior assumptions about quantities and quality of inputs especially for seed, planting material, fertilisers, pesticides, herbicides, etc.
16	Cultivation practices	Preparation of land for irrigation including clearing

	Heading	Description
		Tillage operations (including duration for ploughing, leveling, etc.)
		Fertiliser application (timing and methods), weeding, crop protection, harvesting and processing
17	Livestock	For milk or meat, manure, forage requirements, including crop by-products, field grazing, zero grazing, feedlots, etc.
18	Associated rainfed areas	Influence of land utilisation type on competing dryland agriculture, forestry or agro-forestry
19	Yields and production	Yields per unit area on S1 land (ceiling values for relative yield).
		Yields per unit of water (per m ³) especially during periods of water shortage
		(Specify mean yields with confidence limits, or ranges suitable for economic and financial sensitivity analyses)
		Land equivalent ratio, income equivalent ratio
20	Environmental impact	Public health problems (e.g. Ross River Fever, diseases transmitted by water)
		Downstream effects on water supply and quality, siltation, flooding, etc.
		Effects on wildlife conservation
21	Economic information	Market prices, input costs and availabilities, subsidies, credit

Next, select the land qualities relevant to each land use. Some common land qualities employed in land evaluation for agriculture have been listed (see *Table 27.2*). Make sure you address all factors that influence the success of a land use and be aware that several of the biophysical land qualities require information beyond that addressed in these *Guidelines* (e.g. relating to pests, diseases, infrastructure, tillage practices, agronomy, silviculture). When the selection is complete, prepare a table of requirements for each land use – the requirements need to be expressed in terms of land qualities and characteristics. This step is often the most difficult because to define land suitability you must set class limits for each land quality. Common problems include the following.

- Lack of information – there may be little experience with particular combinations of land qualities and land uses so it is difficult to assign ratings. This is most common with new or untried systems of land management (e.g. new crops).
- Interactions between land qualities – land qualities in theory are independent of each other but in practice interactions occur (see *Developments*). For example, crop growth can be affected by interactions between salinity and water availability.
- Judging the boundary between suitable and unsuitable classes – this limit often attracts close scrutiny and it can be difficult to specify because it depends on the land manager's expertise. For example, a skilled and conservative land manager may be able to profitably manage a land unit without degrading it even though it borders on the unsuitable for the stated use. In contrast, a cavalier manager may lose money and degrade the same type of land.
- Inadequate description of the land utilisation type – minor changes to management practices can change the rating for a given land unit but it is sometimes difficult to include or describe these adjustments during assessment.

- Defining acceptable rates of degradation – assessments of land suitability are made on the basis that land management is sustainable. This is easy to say but hard to do. For example, virtually all systems of agriculture in Australia have rates of soil erosion above the natural baseline and defining an acceptable rate is controversial because our rates of soil formation are so slow (e.g. Beckmann and Coventry 1987; Edwards and Zierholz 2000). Many established systems of land use are unsustainable when viewed over decades and centuries. This conclusion will be strongly contested by land owners in most regions with established patterns of land use.

With this background, when setting class limits make sure you declare all assumptions and recognise limits of knowledge. There are several other issues to consider, particularly when dealing with crops.

The values for defining class limits may be qualitative or quantitative, but aim to achieve equivalence between land qualities. For example, the subsoil pH values that define Class S3 for crop production should have about the same effect on yield as the corresponding values for salinity. Gather local knowledge wherever possible but understand that crop requirements may not be documented for the varieties grown in your study region. Furthermore, generic guidelines, such as those used in the databases of environmental requirements of crops (FAO 1998), may not apply locally because of differences in management or crop varieties.

Many land qualities may be relevant but assessing them all is not feasible. In these cases, rank qualities by importance and take into account the relative effect on the land use in question, the variation of the quality across the survey region, and the cost of assessing the quality.

Aspects of climate are important land qualities, particularly in studies of large extent. For example, suitability for a particular crop depends strongly on mean annual rainfall, daylength, growing season, temperature and frosts. In studies of small regions, spatial variations in climate may be too small to affect the land utilisation type, so climate is effectively built into the definition of land utilisation type. For example, it may be defined as 'dryland cropping with mean annual rainfall of 350–600 mm/yr'. When variations are significant, they are not usually strongly correlated with the land units from the land resource survey, except in the case of frost incidence, where landform can be significant (e.g. frost hollows).

The following example illustrates one option for reducing the complexity of suitability assessment. Van Gool and Moore (2005) had to assess the suitability for common crops across the wheatbelt of Western Australia. The crops (wheat, barley, oats, narrow-leaved lupins, field peas, canola, chickpeas, faba beans) were those suited to extensive management (i.e. units of hundreds of hectares) in zones with mean annual rainfall of about 350–600 mm. Separate land suitability tables could have been prepared for each crop taking into account their tolerances to soil properties such as pH, salinity and waterlogging. However, as this was too cumbersome for strategic planning, a single table was constructed for a wide range of crops (Table 27.5).

Adjustments were made to the suitability ratings to cater for local cropping practices. For example, the Esperance Sand Plain is a very productive region for cropping despite a high risk of wind erosion. In this case, the inclusion of soil conservation measures creates a new land utilisation type – dryland cropping with conservation measures – and a new suitability table. Separate land utilisation types for specific crops are necessary if their land resource requirements differ markedly from the general group (and if there is sufficient information at local and regional scales to warrant the division). Avoid implying a greater level of accuracy than the survey data warrants. Test this by listing different crop requirements and then highlighting major differences. Thus, wheat cropping was separated from oats in our example because the latter is more tolerant of waterlogging, acid soils, low temperatures and poor seedbed preparation (Table 27.6).

Table 27.5 Land suitability for dry land cropping (van Gool and Moore 2005)

Land quality (suitability subscript)	Land suitability class				
	S1	S2	S3	N1	N2
Flood hazard (<i>f</i>)	Nil, low		Moderate	High	
Land instability (<i>c</i>)	Nil, very low, low		Moderate	High	
pH 0–0.1 m (<i>zf</i>)	Neutral, slightly acid	Moderately acid, moderately alkaline	Strongly acid, very strongly acid	Strongly alkaline	
pH 0.5–0.8 m (<i>zg</i>)	Neutral, slightly acid	Moderately acid, moderately alkaline	Strongly acid, strongly alkaline	Very strongly acid	
Phosphorus export (<i>n</i>)	Low	Moderate, high	Very high	Extreme (very high)	Extreme
Rooting depth (<i>r</i>)	Deep, very deep	Moderate	Moderately shallow		Shallow, very shallow
Salinity hazard (<i>y</i>)	No risk		Partial risk	Moderate risk, high risk	Presently saline
Salt spray exposure (<i>zi</i>)	Not susceptible			Susceptible	
Surface salinity (<i>ze</i>)	Nil		Slight	Moderate	High, extreme
Soil structure decline (<i>zb</i>)	Low	Medium	High		
Soil water storage (<i>m</i>)	High	Moderately low, moderate	Low	Very low	
Soil workability (<i>k</i>)	Good	Fair		Poor	Very poor
Subsurface acidification (<i>zd</i>)	Low	Moderate	High, presently acid		
Subsurface compaction (<i>zc</i>)	Low	Moderate, high			
Trafficability (<i>zk</i>)	Good	Fair		Poor	Very poor
Water erosion (<i>e</i>)	Very low (low)	Low	Moderate	High	Very high, extreme
Water repellence (<i>za</i>)	Nil, low	Moderate, high	(high)		
Water-logging (<i>i</i>)	Nil, very low	Low	Moderate	High	Very high
Wind erosion (<i>w</i>)	Low	Moderate	High, very high (moderate)	(High)	(Very high), Extreme

Parentheses () indicate adjustments for traditional tillage.

Table 27.6 Land use requirements for wheat and oats in southwestern Western Australia (Moore 1998)

Quality			Wheat requirement	Oats requirement
Important qualities				
1	<i>w</i>	Wind erosion	Plants sensitive to sand-blasting when young	Similar
2	<i>e</i>	Water erosion	Not generally a production issue	Similar
3	<i>n</i>	Phosphorus export	Not generally a production issue	Similar
4	<i>r</i>	Unrestricted rooting depth	Can yield reasonable crops on shallow soils	Possibly similar. More tolerant of chemical restrictions, less of physical
5	<i>m</i>	Soil water storage	Tolerant of moisture stress. Production declines if soil water storage is <30–40 mm/m.	Less tolerant of moisture stress
6	<i>ze</i>	Secondary surface salinity	Moderate tolerance if $EC_e < 400 \text{ mS/m}$	Similar
7	<i>y</i>	Salinity risk	Not a current production issue	Similar
8	<i>zf</i>	pH 0–0.1 m	Varies with variety, but tolerates a wide range of pH (pH_{Ca} 4.5–9) with yield reduction at both extremes	Slightly less sensitive to low pH than wheat, but less tolerant of sodic alkaline soils
9	<i>i</i>	Waterlogging	Water-logging significantly reduces yield	Tolerant of water-logging
			Young plants most sensitive	
10	<i>k</i>	Soil workability	Use generic values for cropping	Similar (more tolerant of poor seedbed preparation, but still reduces yield)
11	<i>zi</i>	Salt spray exposure	Not applicable	Not applicable
12	<i>f</i>	Flood risk	Use generic values for cropping	Similar
Desirable qualities				
1	<i>za</i>	Water repellence	Management issue – reduces germination	Similar
2	<i>zb</i>	Soil structure decline	Management issue – reduces yield	Similar
3	<i>zc</i>	Subsurface compaction	Management issue – reduces yield	Similar
4	<i>zd</i>	Subsurface acidification	Management issue – reduces yield, costly to overcome	Similar
5	<i>zg</i>	pH at 0.5–0.8 m	Management issue – reduces yield (similar to pH 0–0.1 m but mature plants are less sensitive)	Management issue – reduces yield (similar to pH 0–0.1 m but mature plants are less sensitive)

Assessment based on existing surveys

The FAO *Framework* specifies data requirements through description of the land use and land qualities. A major advantage is clearer definition of survey objectives. However, evaluations often rely on information from several existing surveys and other sources on climate and terrain. Many of the problems listed in Chapter 26 are then encountered. A combination of local knowledge and technical expertise can overcome some of these information gaps. Comparing ratings by van Gool and Moore (2005) with other land resource surveys illustrates some of the challenges in relation to wind erosion (Tables 27.7 and 27.8). First was the issue of correlating different ranking systems from previous studies – high risk of wind erosion in one was equivalent to moderate to very high risk in another. The level of detail is also important. If the system of lesser detail is chosen, in this case the 3-level rating of Rogers (1996), then the detail inherent in the other systems is lost during correlation. Where wind erosion risk is a major limitation this could result in insufficient detail for the evaluation. If the system of Tille and Lantzke (1990) were chosen, then it is unclear whether an assessment of high risk by van Gool and Moore (2005) should be assigned to the high or very high rank. Class limits also create confusion, as shown in Table 27.8. In this case, very high risk according to van Gool and Moore (2005) could be moderate or high in the system of Rogers (1996).

van Gool and Moore (2005)	Susceptibility to wind erosion	Low	Moderate	High	Extreme
Wells and King (1989)	Wind erosion risk	Very low, low	Moderate	High, very high	Very high
Tille and Lantzke (1990)	Wind erosion hazard	Slight, low	Moderate, medium	High, very high	Very high, severe, extreme
Rogers (1996)	Wind erosion – degradation risk	Low	Moderate	Moderate, high	High

van Gool and Moore (2005)	Susceptibility to wind erosion	Low	Moderate	High	Extreme
Rogers (1996)	Wind erosion – degradation risk	Low	Moderate	High	

A rule of thumb is to retain all existing ratings, and to divide ratings where possible, even if such divisions are hard to justify and difficult to make consistent. It is simpler to regroup information than to divide it when at some later stage, it is required to improve the evaluation.

Map units, land units and proportional mapping

Conventional surveys often adopt some form of proportional mapping. Here land units are described in terms of some unmapped components; they are described as occupying a percentage of the map unit but not individually delineated. For example, streamlines may occupy only 5% of a land unit, so their susceptibility to water erosion is hidden in a map that only

describes the average condition. In contrast, proportional mapping can identify even very small areas that are susceptible to water erosion. Other localised features of importance include dryland salinity, riparian zones, rock outcrop, highly permeable zones and disturbed land. Proportional mapping allows variation within map units to be shown. It provides a more useful description of the land unit for land management than one giving only average values. In many surveys, the unmapped components are land facets (see *Table 13.2??*) defined at one or two levels of detail. Make sure landscape features of restricted extent (but of practical significance) are accurately recorded, particularly when the information forms part of a hierarchical system of reporting. Summaries based on average values of map units are often misleading and important management issues can be under-reported or missed altogether.

Developments

Strengths and weaknesses of FAO-style assessments

The FAO *Framework* espoused principles that were adopted by survey organisations around the world. There were clear benefits in Australia.

- ▶ Land suitability was assessed and classified with respect to specified kinds of use (e.g. Rowe et al. 1981) as opposed to a single scale of ‘goodness’ of land (c.f. USDA land capability).
- ▶ Evaluations took into account the physical, economic, social and political context of the region concerned.
- ▶ The *Framework* reinforced the importance of an interdisciplinary approach to land evaluation that was already well established (e.g. Christian and Stewart 1968).
- ▶ The concepts of land characteristics and qualities forced survey organisations to reconsider their methods. Maps and reports started to emphasise predictions of individual attributes of soil and land rather than taxonomic classes.
- ▶ The physical principles underlying assessments became explicit because the relationships between calculated land qualities and suitability ratings had to be recorded (e.g. Wells and King 1989). This process encouraged technical scrutiny, revealed weaknesses in existing rules-of-thumb, and highlighted deficiencies in data (e.g. lack of data on soil hydraulic properties).

Several of the disadvantages of FAO-style assessments have already been mentioned. It is important to discriminate between disadvantages of the *Framework* and weaknesses in its application.

FAO-style assessments (e.g. Dent and Young 1981; FAO 1976, 1983, 1984, 1985, 1991, 1993; Rowe et al. 1981; Wells and King 1989; Land Resources Branch Staff 1990) have several perceived weaknesses.

- ▶ Assessments of land suitability depict crisp classes with sharp boundaries when, in reality, variation is continuous and there are degrees of membership to classes (e.g. Triantafyllis and McBratney 1993).
- ▶ Land suitability is usually expressed in static terms and seasonal or longer-term variation is ignored.
- ▶ Land qualities are meant to influence land use in a distinct manner but in reality there are interactions and correlations between various land qualities.
- ▶ Assessment proceeds land unit by land unit, and this can fail to account for aspects of land use where adjacency or position in the landscape is important.
- ▶ The uncertainty of assessments is rarely stated.

- ▶ The final result – a map of land suitability – often fails to provide the land manager or planner with the information they need. In particular, options for management are often lost in the final ratings (see *Assessing the impacts of land management*).
- ▶ Assessments do not address the question of land allocation, although an optimal land use is often implied simply by giving land units a high suitability rating.

There are several other weaknesses with FAO-style assessments that have more to do with implementation or other developments. The critique by van Diepen et al. (1991) identifies several of these and the most pertinent to Australia are as follows.

- ▶ Confusion over terms land capability and land suitability – several agencies use the term land capability for the same concept defined as land suitability by the FAO.
- ▶ Land quality and soil quality are confusing terms for many people and they have now assumed a more general meaning that is even less helpful. The terms are often used in relation to broad and ill-defined concepts such as soil health (e.g. Doran 2002).
- ▶ Assessments are sometimes applied in a mechanical manner independent of the target audience when what is needed is establishing a close dialogue with users.

Infusing quantitative methods

Critics of the FAO *Framework* argue that, although it is outdated from an operational point of view, it may still have a function as background philosophy (e.g. van Diepen et al. 1991). Our view on its legacy is more positive. The FAO *Framework* exhibits value in its own right and in many circumstances it still provides a logical and coherent basis for land evaluation, especially when resources are limited and simulation modelling and quantitative analysis are not feasible (e.g. for local zoning). More significantly, it provides context and a natural starting point for quantitative land evaluation because various steps in the *Framework* can be replaced with more sophisticated methods of analysis.

The explicit nature of the FAO *Framework* makes codification a natural progression. The Automatic Land Evaluation System (ALES) of Rossiter (1990) is a good example. ALES is a computer program for building expert systems that adhere to the FAO *Framework* (Rossiter 2001). The system has several components that provide:

- a means for describing the proposed land uses
- a database to help describe the land units to be evaluated
- an inference mechanism to relate these two and produce suitability ratings
- facilities for understanding and adjusting assessments.

ALES can be linked to a variety of geographical information systems (GISs) and this allows land evaluation to be highly interactive. The system also automates many of the repetitive steps in land evaluation. Unless you have a better system, use ALES to implement an FAO-style assessment and consult Rossiter's online compendium of soil survey and land evaluation information (Rossiter 2006).

The FAO *Framework* was important for guiding the incorporation of simulation models into land evaluation. This progression is clear in Bouma and Bregt (1989) and Bouma (1989a,b). These studies demonstrate how qualitative estimates of land qualities, such as those controlled by soil–water balance, can be replaced by dynamic estimates from simulation models.

Finally, the FAO *Framework* was important in securing a more interdisciplinary approach to land evaluation. The integration of economic principles is notable; for example, Rossiter (1995) and Johnson and Cramb (1991, 1996) showed how to incorporate risk analysis, simulation modelling and economic assessment. These were important steps towards more quantitative land evaluation (see *Chapter 28*).

Assessing the impacts of land management

Conventional assessments of land suitability do not provide land managers with much guidance on optimal strategies for land management or their likely consequences. Many practical aspects of land management depend on the soil–water regime and its interaction with plant growth (e.g. predictions of: crop yield, deep drainage, fertiliser response, erosion, trafficability). Here simulation modelling is necessary (see *Chapter 28*). Similarly, the *FAO Framework* does not provide a simple means for assessing the impacts of land management at broader scales because assessments always assume land use is sustainable.

Smith et al. (2000) adopted features of the *FAO Framework* in their Threat Identification Model (TIM). This has been subsequently developed to incorporate standard methods for risk assessment and Bayesian methods for data analysis. The resulting Land Use Impact Model (LUIM) is proving to be useful for the planning and management of natural resources. LUIM provides a logical pathway for analysing the impacts of land management and the following is summarised from MacEwan et al. (2004).

LUIM enables assessments of the risk posed to land by any threatening process. The components of risk are shown in Figure 27.2. Risk is the product of the likelihood of an event and the consequence suffered if the event occurs. The likelihood that land will be degraded depends on its susceptibility to a particular threatening process and the role a given practice of land management has in causing the process. The consequence of a threatening process depends on how incapacitated the land becomes should that form of degradation occur (i.e. its sensitivity) and the economic and environmental value of the land. The assessment of value extends to off-site assets. MacEwan et al. (2004) provide an example where each component of risk (i.e. each box in Figure 27.2) is mapped. Land resource surveys provide the maps of susceptibility and these are combined with land management surveys (see *Chapter 9*) to map likelihood. Expert panels provide ratings of this likelihood. The analysis in LUIM involves construction of a Bayesian Belief Network.

The right-hand side of Figure 27.2 is more difficult to analyse. One must determine how much a given land use is affected by a specified severity of degradation, and this requires an understanding of how land recovers from degradation (e.g. erosion, acidification, compaction). Finally, the valuation of assets may range from a simple estimate of market value of the land through to a more sophisticated estimate of capital value with economic, social and ecological components.

LUIM provides a convenient framework for integrating biophysical, social and environmental aspects into land evaluation. Software for the Bayesian analysis has been implemented within a GIS and is available from the developers (Carl Smith, pers. comm. 2006). Initial experience with LUIM is encouraging, especially for catchment management at regional scales.

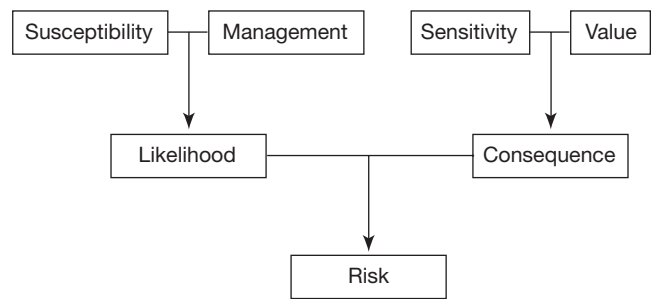


Figure 27.2 Components of risk posed by any hazard.

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Quantitative land evaluation

AJ Ringrose-Voase

Introduction

Quantitative land evaluation is defined broadly to include any analysis of land behaviour involving quantitative inputs and outputs. This includes quantitative analogues of conventional assessments of land suitability, as well as evaluations of aspects of land behaviour using simulation models at a range of scales (from the site through to the hillslope, small catchment, large catchment and continent). As with conventional land evaluation, quantitative land evaluation aims to use data from surveys to help land planners and managers improve their decisions. Quantitative evaluations use models to relate land attributes estimated during survey to land behaviour. They have several potential advantages over conventional land evaluation:

- they encourage the use of measured land characteristics
- land qualities are assessed using explicit relationships between various land attributes and their effects on the behaviour of the land (this avoids the setting of arbitrary thresholds for each attribute)
- models can explicitly deal with interactions between different land characteristics and qualities
- depending on the model used, dynamic assessments are made in different years and seasons – hence, the probability of particular events occurring can be estimated.

Quantitative land evaluation places new demands on surveyors because models require inputs relating to the functional behaviour of soils and landscapes (e.g. storage and transport of water, nutrients, solutes, sediments) rather than soil types (McKenzie et al. 2000).

Models

Models fall into two broad categories, although in reality most models contain elements of both.

- 1 *Empirical models* are based on statistical relationships between observed behaviour and land attributes
- 2 *Process models* try to encapsulate the understanding of processes derived from scientific research. Often they try to allow the system to be viewed as a whole by combining process understanding from different disciplines.

At the point scale, models using statistical relationships to predict crop yield from annual rainfall or soil factors or both (e.g. Dumanski et al. 1987, 1989) are at the empirical end of the

spectrum. At the process end, there are crop models such as APSIM (McCown et al. 1996; Keating et al. 2003) and PERFECT (Littleboy et al. 1989) that simulate crop growth, the water balance, crop residue breakdown and other relevant phenomena.

At the catchment scale, empirical models such as IHAACRES (Jakeman et al. 1990) predict stream flow from rainfall using relatively few parameters that are calibrated using historical stream flow and rainfall data. MIKE-SHE is a process-based model that simulates the major land-based hydrological processes at a catchment scale (Danish Hydraulic Institute 1998).

Models at each end of the spectrum have different strengths and weaknesses, supplying them with different roles.

Empirical models

Empirical models can also be viewed as descriptive models because they are based directly on observational data (Thornley and Johnson 1990) and do not deal with the mechanisms causing the behaviour (Penning de Vries et al. 1989). They often show good statistical fits to the data used for verification, implying they have good predictive capabilities. In terms of the number of parameters they require, they are usually economical.

Static empirical models are used to predict land behaviour from land attributes, and can be grouped into threshold models and regression models (Burrough 1989). Bouma and van Lanen (1987) refer to them as class transfer functions and continuous transfer functions respectively. In threshold models, the output (e.g. land suitability for a given land use) depends on whether observed land attributes are greater or less than certain threshold values. The thresholds for different attributes need to be applied sequentially. This is the process involved in the conventional assessment of land suitability (see *Chapter 27*). Regression models relate land behaviour to static land attributes using statistical relationships. For example, Dumanski et al. (1987, 1989) predicted mean crop yield from several land attributes.

Dynamic empirical models estimate land behaviour from a sequence of weather data. Model parameters are derived by calibration in which model outputs are statistically fitted to measured data; for example, predicted stream flow is fitted to measured flow. In some models the parameters are simply fitted constants, without any physical meaning. In others, the model may have been designed so that the parameters have physical meaning. However, their actual values are not directly measured and the fitting process may result in parameters not reflecting their intended meaning. In either case, statistical models cannot make predictions for conditions outside the range of conditions used to develop the model, simply because their predictive ability is compromised if the system changes substantially.

Such models have little power to explain the reason for a given output and may not be able to make predictions about hypothetical situations. Thus, an empirical model of stream flow that is calibrated under current land use may be incapable of predicting flow after widespread afforestation or deforestation. Similarly, empirical static models of crop yield cannot be used to forecast yield in regions different from where they were developed.

Clearly, models whose parameters are not physically based have little potential to add value to land resource survey because they cannot use survey data as inputs.

Process models

Process models consist of mathematical descriptions of a system's underlying mechanisms – the processes that cause it to behave as it does. The strength of process models is their ability to explain the effect of various land attributes on behaviour in terms of current understanding of the relevant process or processes (Penning de Vries et al. 1989). Process models encapsulate understanding gained from scientific experiments and trials, often at intensively measured sites. They frequently aim to integrate knowledge about different components of a system into the

system as a whole; they thereby capture not only the individual component processes, derived from work in various disciplines, but also the interactions between the processes. For example, a model might simulate crop growth and yield based on known effects of weather, soil water and farmer-applied nutrients (van Diepen et al. 1991). Calculations are made at various intervals – from less than one day up to one year (one day is standard). Such models might use historical daily weather data from relevant meteorological stations, local knowledge of farm management practices, and soil and other landscape data obtained from land resource survey.

Surveys of land resources provide input data that allow process models (embodying the results of intensive research into the underlying processes) to be extended beyond their initial domain to the wider landscape. The potential for process models in land evaluation was realised by Nix (1968), but applications have become common-place only since the mid-1990s.

Process models operate at a variety of scales. Many models for predicting plant growth and soil water balance operate at a point scale (Rossiter 1996). They ignore position in the landscape and hence they leave out the movement of materials laterally across the landscape through processes such as runoff, soil erosion and groundwater movement. However, where these processes are important, or where the aim is to predict how the landscape as a whole behaves, it is necessary for the model at one location to take into account what is happening at other locations (i.e. to be spatial). This can be done by dividing the landscape into two- or three-dimensional finite elements that are considered internally homogeneous. The model is parameterised and run for each element, taking into account movements of materials from neighbouring elements and passing materials to neighbouring elements. Such elements can be square or irregular, tessellating the landscape as in distributed parameter models such as MIKE-SHE and TOPOG (O'Loughlin 1986; Vertessy et al. 1993). The parameterisation and computational demands of such models are often considerable and sometimes impractical.

A remedy is to make the elements larger polygons enclosing fairly homogeneous areas. They can be defined as land facets or, as in the catchment framework of Paydar and Gallant (2003), by landscape position. Because there are fewer elements, the computational demands are eased, but care must be taken to allow for the difference in areas of neighbouring units (and for the interfacial length between them) when passing materials from one to the other. The lessened parameterisation demands better match the scale at which most survey data are available. To cope with short-range variation, the elements can be considered to have a defined range of attribute values; the model is then run several times for each element using different sets of attribute values, with the final result being an area-weighted average (Ringrose-Voase et al. 2001).

Process models involve calculating the state of various attributes of a system over time (de Wit 1982). Thus, *state attributes* describe a system at any given instance (e.g. the amount of soil water and plant biomass). The model calculates changes in state attributes in response to the *driving attributes* of the environment operating on the system. Such attributes include the amount of rain and radiation over specific periods or the maximum and minimum daily temperature. In addition, there are management drivers, such as the sowing of crops at particular times and the amount and timing of fertiliser applications. A state attribute in one model component (e.g. water content in a soil water submodel) can become a driving attribute in another (e.g. soil water content in a crop growth submodel). This is how interactions between the various processes that make up the whole system can be calculated.

The rate at which a state attribute responds to the drivers depends on *rate attributes* that describe the fluxes of materials and energy between state variables, for example the accumulation rate of biomass in response to existing leaf area, radiation, water and carbon dioxide, or the flux of water through the soil in response to rainfall and evapotranspiration. The rate attributes are calculated from the current state and driving attributes according to rules based

on knowledge of the processes taking place. The rate and state variables are constrained by various *constant attributes* of the system. These include the plant available water capacity of the soil, soil hydraulic conductivity, soil pH and organic matter, slope and aspect.

An important aspect of process modelling is that it can provide dynamic results, whether or not the results are expressed as a time-series. For example, conventional land evaluation may allocate static classes of suitability for a particular type of cropping system and give some idea of the expected yield range – the inputs and outputs are static (Rossiter 1996). Simulation modelling of the same cropping system using historical weather data shows how the yield varies from year to year. Because yield responds to seasonal rainfall in a non-linear way, the yield calculated from the mean seasonal rainfall often overestimates or underestimates the mean of the yields calculated for a sequence of seasons (de Wit and van Keulen 1987). Such a model has dynamic inputs, but static outputs (mean yield) (Rossiter 1996). Results can be better presented as a probability distribution showing the probability of exceeding a particular yield.

Expressing results in terms of probabilities helps determine whether a production system is viable on the basis of its year-to-year cash flow, not simply on the expected profits based on an average yield. This capability is particularly important in climates with highly variable annual rainfall and consequent annual productivity (Thomas et al. 1995). Wösten and Bouma (1985) used simulation modelling of the soil moisture regime to show the probability of various land units being trafficable at various times of year, and van Lanen and Bouma (1989) did likewise for soil moisture deficit and adequate soil aeration.

Dynamic process modelling usually involves simulation of several components of a system. This allows analysis of trade-offs between production and the environment. Thus, a crop model might provide information on yield and profit while at the same time simulating runoff, drainage of water below the root zone or leaching of nutrients. This allows, for example, the trade-off between the profitability of cropping systems using different fertiliser levels and nitrogen leaching to be investigated.

Although there are simulation models concerning many aspects of land behaviour, the soil water balance is central to most (Bouma 1989). This involves estimating infiltration of water into the soil, water movement between soil layers, water use by crops and evaporation from the soil surface, and drainage from below the root zone or capillary rise from groundwater. There are two broad ways of simulating the water balance as follows.

- 1 *Mechanistic type models* (based on the Richards equation) – these estimate water movement using water potential gradients between layers. They require information on the soil water characteristic (the soil's inherent relationships between soil water potential and water content), and the relationship between hydraulic conductivity and water potential.
- 2 *'Bucket' type models* – these treat the soil, or each layer of it, as a bucket whose primary attribute is its available water-holding capacity. Infiltration and movement from other layers fill up the bucket while evapotranspiration, drainage and movement to other layers empty it. When the bucket is full, water moves to the next layer down. Such models are primarily concerned with conserving mass and do not explicitly consider soil water potential or hydraulic conductivity. These types of models usually require fewer parameters than the Richards equation type.

McKenzie et al. (2002) provide guidelines for measuring the physical properties required by each type of model and there are pedotransfer functions for estimation (see *Chapter 22*). In crop models, the daily water balance is used to predict crop growth and, eventually, yield. Van Diepen et al. (1991) point out that modelling the effects of lack of water on crop growth and yield are generally more advanced than modelling the effects of excess water. Apart from estimating crop yields in response to various management options, they are also increasingly

being used to estimate runoff and drainage below the root zone, often in relation to off-site impacts on salinity or stream flow and quality.

The explicit nature of process models is useful for comparing the likely outcomes of different scenarios. Individual attributes in the model can be manipulated to analyse their effect on outcomes, taking into account their interactions with other attributes. This could involve predicting the performance of different crops on the various soils in a survey area. Different land management options, such as varying crop sowing date or fertiliser rates, can be investigated to see how crop yield depends on soil type. This gives such models an analogous role to traditional land evaluation: they use land attributes gathered by land resource survey, combine them with knowledge of land behaviour, and suggest improved management options for land in the region.

Increasingly, such models are being incorporated into spatial frameworks for use at wider scales, allowing an investigator – by simulating changed land uses in various parts of the landscape – to see the effects of changing land use on stream-flow or groundwater levels (e.g. Paydar and Gallant 2003). Such models are multiarea assessments (as opposed to single area) in Rossiter's (1996) scheme (see *Chapter 27*, Table 27.1).

Benefits accrue from achieving a closer collaboration between process modellers and surveyors (van Diepen et al. 1991). Surveyors understand the spatial distribution of parent materials, soils and vegetation. Modellers and other scientists (e.g. agronomists, soil physicists, chemists, biologists) often understand processes in great detail but, by necessity, at only a few locations within a given landscape. Both groups need to recognise that the other has something to offer. 'Process' scientists need to understand landscapes to apply their knowledge at a broader scale. Similarly process models offer surveyors a more rigorous way of evaluating the implications for land management of variation within the landscape. A dialogue between the two groups will make each party aware of the requirements and limitations of the other.

Model complexity and uncertainty

Models have two main sources of uncertainty: systematic error and parameterisation error (Walker and Zhang 2002). The former arises from the simplifications and approximations made by the model, the latter from errors and uncertainty in the input parameters. To reduce systematic error, more detail can be added to a model by including more processes and describing them and their interactions more realistically. For example, the soil water balance can be better described by changing from a simple bucket model that includes only the water holding capacity of the root zone, to a layered bucket model that includes the storage capacities of different soil layers. Further improvement can be made by changing to a Richards equation-based model that uses the water retention curves and hydraulic conductivities of each layer. However, as the model becomes more complex, the number of input parameters increases. Each of these parameters has some uncertainty in its measurement or estimation, so that the parameterisation error generally increases with complexity. Burrough (1989) refers to a 'parameter crisis' where the difficulties of estimating many parameters over the survey region, combined with their short-range variation and errors in measurement, can make the output of such models very uncertain. This compromises their predictive ability, and van Diepen et al. (1991) state that even process models usually require some statistical calibration to improve their predictive capability.

Minimising uncertainty requires achieving a balance between these multiple sources of error (Figure 28.1). In general, the more limited the availability of input data, the more the balance should be shifted towards simplicity. One problem in achieving a suitable balance between complexity and simplicity is that models are often developed from intensive observations at

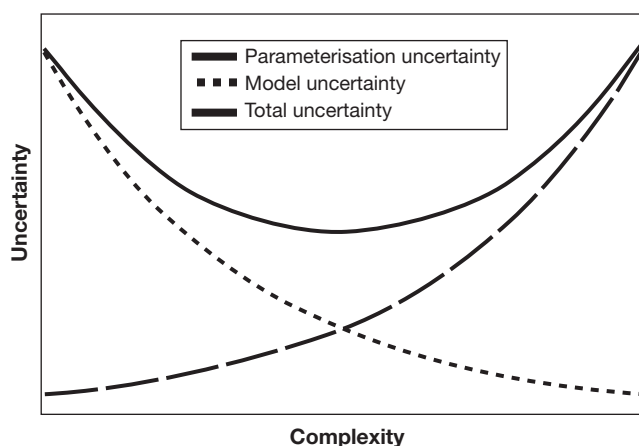


Figure 28.1 Relationship between uncertainty and model complexity (after Walker and Zhang 2002).

experimental sites and researchers are often reluctant to leave out details they have spent much time investigating. Moreover, while the data required for a complex model can be measured at experimental sites, they are often too expensive to collect for routine survey. Little is gained by having a model that captures every nuance of the processes involved, but which requires many input parameters that are too difficult or expensive to measure or estimate in a survey (de Wit and van Keulen 1987). Models for land evaluation should take into account the limitations of the data available from survey to achieve a compromise between capturing the essential processes and availability of input data. For example, a crucial part of water balance models is partitioning rainfall between runoff and infiltration. Some models calculate infiltration during rainfall in great detail. They require knowledge of the relationships of both hydraulic conductivity and water content to water potential, together with surface conductance and surface detention and how these change with cumulative rainfall. Measuring these parameters is beyond the scope of a survey program. In addition, because rainfall intensity is important, the model is best used with subdaily rainfall data, which are rarely available. It makes more sense to use a more approximate method such as the USDA curve number (USDA Soil Conservation Service 1972), which can be estimated using a simple score of surface condition and slope (Littleboy 1997).

Additional complexity occurs when a model is run for many locations in the landscape with the inclusion of interactions between locations. For example, Paydar and Gallant (2003) used a point-scale crop model (APSIM) to simulate crop behaviour and water balance in a catchment. They modified the model to allow lateral movements of water, calculated for the upper parts of the landscape, to become inputs lower in the landscape. In such cases, errors (both model and parameter) generated in the upper parts of the landscape increased errors in the lower parts.

In addition to balancing the complexity of the model to the data available, the complexities of different components of the model need to be balanced. In the above example, having a very detailed infiltration model may be pointless in a cropping context if the breakdown of crop residue and its effect on surface cover is inadequately modelled. The output will only be as reliable as the least reliable component. Furthermore, the data demands for overly detailed components can lead to unnecessary time and expense in obtaining them during the survey. Thoroughly test the sensitivity of model outputs to the various components in the conditions found in the survey area. This will ensure that each component receives appropriate attention.

Input data for models

Providing spatial data for quantitative land evaluation involving models is a challenge.

- ▶ The necessary parameters are frequently not those measured during conventional survey.
- ▶ The main product of a conventional survey is a map showing land units, which may not present the underlying data in an optimal form for modelling.
- ▶ The uncertainties of surveyed parameters are rarely given. In quantitative survey, the emphasis is on the prediction of individual attributes, making it better suited to providing data for modelling.

What attributes?

For most models likely to be used for land evaluation several types of information are required: constant, initial values of state and driving attributes.

Constant attributes constraining state or rate attributes include many soil hydraulic, physical and chemical properties, slope and aspect. Many can be sourced from surveys, in which they have either been directly measured or estimated from other land attributes using pedotransfer functions.

Initial values of state attributes, such as soil water content, soil pH and organic matter, are required to define the system at the start of simulation. They are then modified by the model. Rapidly varying attributes are usually set to an arbitrary value. For example, soil water content could be set to wilting point throughout the profile. Such arbitrary setting of state variables can lead to initialisation effects on the results, which are best removed by discarding results from the earliest period of simulation. In crop modelling, it is good practice to remove at least the first year's results when conducting simulations over several decades. More slowly changing state attributes, such as soil pH or organic matter, can be set using survey data in cases where the intention is to predict how these attributes might change under different scenarios of land management.

Whether a particular land attribute is used as a constant attribute or as an initial value of a state attribute depends on the model and the aims of the investigation. For example, when studying the effects of different cropping systems on soil hydrology, one might decide to assume that soil pH remains constant. In this case pH is a constant attribute. However, if the aim is to investigate the effects of various types of management on the pH of different soil types, pH would be a state attribute and only its initial value would derive from survey data.

Driving attributes include weather and management inputs. Historical weather data can be obtained from Bureau of Meteorology records for meteorological stations within or close to the survey area. The most commonly required attributes are rainfall, radiation, minimum and maximum temperature and vapour pressure. The most common temporal resolution available is daily, which is adequate for many crop and vegetation models. Where climate is fairly constant over a region, it may be safe to use the same weather data for all locations. However, in most regions this is not strictly the case and weather data for different locations are preferred. The number of stations in a region is likely to be small and unrepresentative of all locations, with upland locations having particularly poor coverage. The Datadrill resource (Jeffrey et al. 2001) provides interpolated daily weather data from 1957 onwards for the whole Australian continent on a 0.05 degree grid. Although the accuracy of Datadrill varies over the continent, it is suitable for most inland cropping regions.

Management inputs describe the way the land is managed or could be managed. For example, crop models require information on what crop species or cultivars are sown and at what density, the dates of the sowing window, the conditions necessary before sowing takes

place, and inputs of fertiliser and irrigation. Information on current practices is usually gathered from local knowledge. For cases in which models are run for subregions to predict outcomes for a whole region (e.g. production of runoff and drainage for a whole catchment), it is necessary to know not only what land uses and management practices are used but where. Land use data showing what type of vegetation occurs over the area can be obtained from land use surveys (see *Chapter 9*). Data on land management practices are not readily available but can sometimes be gathered (ideally at sampling sites) during a survey. This requires interviewing the land manager for each site about details of management. This information can be used to develop some generic management practices for each land use in different parts of the landscape. For example, in the upper parts of the landscape, land mapped as pasture might be permanent pasture used for a variety of animal production enterprises. While the individual types of enterprise cannot be mapped, the proportion each occupies in the pasture map unit could be statistically derived. Pasture mapped in the lower parts of the landscape could be a mixture of permanent pasture and a pasture phase of crop rotations.

Ideally, surveys should be designed to meet the data requirements of the model(s) to be used. Therefore, the first stage in planning a survey specifically for a particular model is to determine the attributes that should be measured. Next, a sensitivity analysis should be undertaken by running the model with the complete range of input parameter values likely to be found within the region.

General purpose surveys are often made with the intention of providing data for as yet unforeseen models, whose detailed requirements are clearly unknown during the survey. Nonetheless, there are some commonly used parameters that are used by most models (see *Chapter 17*, Tables 17.9 and 17.10).

Attribute measurement or estimation

Your chosen input variables will need to be measured or estimated. The choice will depend on cost and the likely pattern of variation across the region. Where there is little short-range variation, using a precise (but expensive) method in relatively few locations is justified. For attributes with large short-range variation, take many relatively inexpensive measurements, even though they will be less precise.

Where such methods are unavailable or too expensive, pedotransfer functions can be used to estimate parameters that are difficult to measure, using parameters that are more easily measured (see *Chapter 22*). This will usually require a more precise, and expensive, method to be applied at a limited number of sites within the survey region, to locally calibrate the pedotransfer function. Effective pedotransfer development requires a large database of measured attributes obtained over a wide range of landscapes. Survey organisations should have an active program to build up such databases by ensuring that the necessary measurements are made at least at some sites within each routine survey (simply because it is unlikely that the number of samples within any one survey will be sufficient to develop pedotransfer functions with wide-spread applicability). One drawback with this strategy is that the time and effort spent on such intensive measurements only bears fruit in the long term and might seem to contribute little to the outcomes of an individual survey.

If the model is very sensitive to certain attributes (those that are too difficult to estimate with sufficient accuracy for the output to be reliable), then the only recourse is to simplify the model so that it requires parameters whose measurement is more feasible. In general, it is better to use a model that relies on parameters with additive attributes. For example, water balance can usually be estimated reasonably well using a 'bucket' model based simply on the (plant-available) water holding capacity of the soil. This is an additive attribute because the mean capacity of a region is simply the arithmetic mean over the area. Thus, if sampling is not sufficiently intense

to capture extreme values, it has little effect on the mean. Bucket models conserve mass but may transfer water at incorrect rates through the soil profile. To make them more accurate, a Richards equation model can be used. However, such models may be highly dependent on hydraulic conductivity, which is not an additive attribute. Small areas with large conductivity values have a disproportionate effect on the mean result. Adequate sampling to 'capture' such large values may be too expensive for any potential gain in model accuracy to be worthwhile.

Many important parameters, both used directly or indirectly via pedotransfer functions, are conventionally obtained from laboratory analysis of disturbed specimens. The expense of multiple laboratory measurements on each soil layer usually leads to a rationing of the number of sites that provide laboratory specimens. Newer methods using mid-infrared and near-infrared spectroscopy have the potential to considerably lower the cost of parameter measurement so that many more sites can be sampled (see *Chapter 17*).

Of particular importance are physical soil attributes such as bulk density, water holding capacity and hydraulic conductivity, since these are required for calculating water balance, an essential component of virtually all models. Unfortunately, these parameters are often difficult to measure in a survey program. Field-based measurements are time consuming compared to routine examination of soil profiles by auger or drill rig. Similarly, laboratory methods require undisturbed specimens that are much more difficult to obtain than bulk samples for chemical analysis. However, the increasing use of process models adds pressure on survey planners to ensure resources are allocated for measurement of these parameters.

Unfortunately, despite their usefulness, many pedotransfer functions for physical attributes become very uncertain if they are not constrained by at least the measurement of bulk density. Make sure bulk density is measured routinely during a survey. Since this requires taking volumetrically intact specimens, it may be worthwhile measuring other physical measurements on the same specimens (see McKenzie et al. 2002).

Another vitally important attribute in most models is the rooting depth or water extraction patterns of various plant species – these affect the total plant-available water holding capacity of the soil. There are no routine methods for estimating this during survey. In field experiments the water extraction patterns of plants are usually estimated by measuring volumetric water content both when the soil is fully wet after heavy rain and has been allowed to drain for a few days, and at the end of the growing season when the soil has been dried to its maximum extent. McKenzie et al. (2002) suggest making these measurements at selected sites in the survey region. If these were selected early enough in the survey, both wet and dry measurements might be feasible by the end of the survey.

Sampling strategies

The sampling strategy to meet the data requirements of process models is likely to differ from that for a conventional survey. The latter emphasises soil morphology and mapping of soil profile classes, measurements of chemical properties are restricted to representatives, and generally there are even fewer, if any, sites where physical attributes are measured. Such a strategy does not provide sufficient data for modelling. Model output for sites that are representative from a morphological point of view might be biased (de Wit and van Keulen 1987). Possible reasons include the following.

- ▶ The parameters important to the model do not correlate with the map units. The assumption that they are correlated is implicit in conventional survey but rarely tested.
- ▶ The model output may be dominated by attributes with non-normal distributions within the map unit. For example, hydraulic conductivity is usually non-normally

distributed so that, where model outcomes depend on hydraulic conductivity, small proportions of a map unit with very high conductivities will tend to dominate the mean behaviour of the unit.

- ▶ Model output may be dominated by non-linear phenomena, in which case 'non-representative' parts of the unit may dominate the mean. In this case, the input data for a 'representative' site may be close to the mean, but not the output dependent on it.
- ▶ The output may be dominated by interactions within the model. Data from 'representative sites' do not allow full exploration of the interactions between different attributes as they vary within a unit, especially where they are non-linear. This negates a key advantage of simulation modelling – the ability to deal with such interactions.

In addition, purposive sampling does not allow estimation of uncertainty.

In short, the emphasis of field work during a survey for modelling should be less on delineation of map units for production of maps (in which land attributes have been interpreted by the surveyor) and more on provision of primary data for 'interpretation' by the model. Quantitative evaluation requires much more direct measurement of soil attributes (McKenzie et al. 2000).

Quantitative surveys (see *Chapters 22 and 23*) are better suited to the needs of modelling – indeed they are often designed with the intention of using modelling to evaluate the survey data. Their emphasis is on the prediction of the spatial distribution of individual land attributes rather than on the distribution multiattribute entities such as soil profile types. Potentially they can overcome the problems associated with conventional survey. Realistically, however, they are still subject to the constraints of what it is possible to measure in a survey context, relative to the input requirements of many models.

Modelling in a survey framework

Input data for modelling can be provided as primary point data, in which case the model is run for each point and the chosen spatial prediction method applied to the output data. This is sometimes referred to as 'calculate then interpolate' (CI). Alternatively the input data can be provided as choropleth maps or as grids after the spatial prediction method has applied to the input data. In this case the model is applied to the predicted parameter values – referred to as 'interpolate then calculate' (IC). The distinction (see *Chapter 22*, shown in Figure 22.3) is important because it affects the amount of modelling required and the way that uncertainty is propagated through the system (Heuvelink and Pebesma 1999).

Conventional survey

Although conventional surveys are not ideal sources of data for modelling, the following strategies make best use of them because most existing land resource information is from such surveys and because conventional methods continue to be used.

Modelling with input data from existing surveys is likely to involve pedotransfer functions. In most cases data will be provided for several 'representative' sites within each land unit. The model can be run for each site in preference to using average values for the land unit. This allows at least some expression of non-linear interactions.

In this case, spatial estimation is via the delineated land units and usually involves simply averaging the model output for all the sites with each unit. If modelling is performed on the individual sites, some indication of the possible range of output values can also be given. If the sites represent a proportion of the area of the land unit, it is possible to calculate an area-weighted mean. However, because the sites were selected purposively, they cannot be used to calculate unbiased estimates of the mean and variance.

Littleboy et al. (1992, 1996) and Thomas et al. (1995) investigated the use of the PERFECT crop model to evaluate suitability for cropping. They determined soil input attributes from soil maps and pedotransfer functions, and slope from digital elevation models. Yield was predicted over 95–100 years using historical data on daily weather. They found good agreement between predicted yield and land suitability classes determined conventionally. Abbs and Littleboy (1998) and Ringrose-Voase et al. (1999, 2003) used similar crop models (PERFECT and APSIM, respectively) to evaluate the long-term mean annual drainage below the root zone for various cropping systems and perennial land uses.

Abbs and Littleboy (1998) used pedotransfer functions to estimate model input parameters from those available in the survey report. Ringrose-Voase et al. (1999) revisited the original sample sites for the major representative soil profiles in the survey report and measured their hydraulic attributes to reduce reliance on pedotransfer functions. This removed or reduced the uncertainty resulting from pedotransfer functions and replaced it with the usually smaller uncertainty associated with measurement.

Thomas et al. (1995) simulated crop production (and profitability) and soil erosion loss for wheat cropping with various inputs of nitrogen fertiliser, and highlighted interactions between profitability and sustainability. Ringrose-Voase et al. (1999, 2003) predicted crop production and profitability as well as deep drainage, and were thus able to demonstrate the trade-offs between them for different land uses on different soil types with different climatic conditions.

In the above examples, the model output was analysed from the point of either:

- how a particular land use performed at particular locations
- which land use performed best at particular locations
- at which locations a particular land use performed best (i.e. a single area assessment) (Rossiter 1996).

Flügel (1997), Ringrose-Voase et al. (2001, 2003) and Paydar and Gallant (2003) attempted to estimate the effect of different land uses for a whole catchment (i.e. the ranges of land uses in each part of the catchment that give the best outcomes in terms of both maximising profit and minimising drainage). These are multiarea assessments (Rossiter 1996) and they aimed to show the relative contributions of various model outputs (excess water or profitability or both) in different parts of the catchment. Ringrose-Voase et al. (2001, 2003) treated each map unit in isolation and ignored lateral movements of water downslope, especially runoff, whereas Flügel (1997) and Paydar and Gallant (2003) went one step further by allowing for lateral movement of water between map units. This allowed them to estimate contributions to streams and groundwater by different parts of the catchment under different land use scenarios.

An integral part of the studies by Flügel (1997), Ringrose-Voase et al. (2001, 2003) and Paydar and Gallant (2003) was the derivation of land units to represent a range of conditions within a catchment. These land units help to reduce the complexity of the landscape and the number of simulations necessary. For example, Ringrose-Voase (2001, 2003) based land units on slope (from a digital elevation model), lithology (from various geology and land systems maps) and climate (from Datadrill), since these correlated well with both soil types and land uses. They used overlays in a geographical information system (GIS) to estimate the proportion of the area of each unit occupied by each soil type and the area occupied by each land use. By multiplying these proportions, they obtained the area proportions of each land use by soil type combination within each unit. Thus, a unit was not considered to be a homogenous entity, but one with a defined range of soil types and climate. They used APSIM to estimate the mean annual drainage, runoff and crop profitability for each climate by soil type by land use combination. The output for each unit was then estimated as the area-weighted mean

drainage, runoff and profit for the relevant multiplicative combinations. By changing the land use proportions for a particular unit, they were able to estimate the effects of land use change on catchment behaviour.

Hybrid surveys

Unbiased sampling of land units mapped by conventional survey provides data for modelling that has better statistical properties. Modelling can be carried out as above on the site data (whether estimated directly or via pedotransfer functions). Spatial prediction is still via the land units, but an unbiased estimate of the mean and variance of model outputs for each land unit can be calculated – this allows more objective comparisons between land units and potential land uses (e.g. whether the differences in simulated behaviour are statistically significant).

An alternative analysis is to first calculate the statistics of each input variable within each map unit (i.e. the mean and distribution) and then perform modelling on the statistics. This is equivalent to performing the spatial prediction before the modelling. A rigorous analysis of uncertainty can be gained using techniques such as Monte Carlo (see *Chapter 24*), in which the statistical distributions for each attribute are used to generate the attributes of many hypothetical sites in proportion to their likely occurrence within the map unit. The model is run for each hypothetical site to estimate the mean and variation of the model output within each unit. The problem with Monte Carlo analysis is that it requires sufficient samples in each unit to estimate the shape of the distribution, although it is possible to assume a shape based on prior knowledge. More importantly, it requires many model runs to cover the full range of combinations. If x values are sampled from the distributions of each input parameter, the number of runs required for n parameters is x^n . This can lead to a prohibitive number of runs, especially for complex models with large numbers of input parameters and large computational requirements per run. Efficiencies can be gained by analysis of the covariances of the input data, which restricts the number of combinations necessary.

A simplification of Monte Carlo analysis is ‘possibility’ analysis, which requires only the possible range (i.e. maximum and minimum values) of each input variable rather than the shape of the distribution. The model is run using all combinations of maximum and minimum values for all the input attributes. For n input attributes this requires 2^n runs. The result is a range of possible output values. If this is done for each unit, it shows whether the land units have any value for predicting model outcomes or whether the ranges of possible output values for each map unit overlap to such a degree with other units that they provide no useful differences.

Quantitative surveys

In general, the needs of a model can be met efficiently by designing a quantitative survey. A choice is required between, before or after spatial prediction (i.e. CI versus IC). With CI the model is run at each sample site using the measured input attributes. The results over the rest of the survey area are then predicted using a method such as environmental correlation (see *Chapter 22*) or kriging (see *Chapter 23*) to produce surfaces showing the output parameters varying continuously over the area. For example, Triantifilis et al. (2001) used gridded survey data to calculate semi-quantitative suitability scores for a range of crops, employing fuzzy logic to describe how close each site was to being suitable. They then interpolated the results over the survey region using punctual kriging to produce continuous suitability surfaces for each crop.

With IC, environmental correlation or kriging is used first to predict the input attributes over the survey region and is followed by modelling across the whole surface. Such an approach may be appropriate for distributed parameter models, such as MIKE-SHE, using regular finite elements. However, for large, complex models where interactions with neighbouring elements

are ignored, it may be better to use CI since the computational requirements for each point may be too large to model output over the entire survey area. IC can be used with relatively simple models, with fewer computational demands. In addition, there is some evidence that CI may perform better than IC in terms of reducing uncertainty (Stein et al. 1991; Bosma et al. 1994).

An example of process modelling using data from a quantitative survey and IC is that of Tickle et al. (2001) who used a forest model, 3PG-SPATIAL, to predict production of native forest covering a 500 km² area with high relief. Land attributes were provided by a quantitative survey (McKenzie and Ryan 1999) that used environmental correlation to predict attribute surfaces covering the survey area. These surfaces had a grain of 25 m. These were used in a configuration of 3PG designed to run as a distributed parameter model within a GIS. The model calculated forest growth and water balance for each 25 m element over 100 years, allowing movement of water between elements. Values of input attributes for each element were taken from the same cell in the attribute surfaces. Growth parameters in the model were calibrated using 16 sites in the survey area and model output was validated against a separate set of sites. Model output consisted of surfaces showing the values of various aspects of crop production on the same 25 m grid. Although the model was similar to many crop models, it was simpler in several respects, which lowered its computational and parameterisation requirements and made it feasible to configure as a distributed parameter model. First, it used a monthly time-step, with monthly weather data rather than daily. Second it used a very simple 'bucket' model for the soil water balance. This illustrates how a compromise can be reached to ensure balance between process and landscape detail.

In many cases a mixture of the two is used. Input attributes that vary over short distances within the survey area are taken directly from sample sites. Other attributes, such as climate or daily weather, which vary more slowly or at least more predictably over the region, might be taken from interpolated data sets. For example, a crop model might be run using soil attributes for each sample site, but with interpolated weather data such as that provided by Datadrill (Jeffrey et al. 2001), since there are likely to be only a limited number of weather stations within the survey area.

Where sampling intensity is low, or the model computationally demanding, or both, another approach is to classify, interpolate and then model. This has similarities to modelling with conventional survey data, but with the important difference that the classification – preferably numerical – is based on parameters relevant to the model. The classification should create classes within which model results are more similar to each other than to results from other classes. If possible, numerical techniques should be used (see *Chapter 21*). The input parameters are predicted over the region and used to delineate map units based on the classification. The results for each unit are determined either by running the model for each sample site within the unit and calculating the statistics of the output, or by running the model on data representing the range of interpolated input attributes for a class using Monte Carlo or possibility analysis (see *Hybrid surveys*).

Model verification

An important aspect of any modelling study is verifying the accuracy of the results. This is especially important when stakeholders might be persuaded, as a result of model output, to make changes to land management that might affect profitability (Comerma and de Guenni 1987). When models are used to analyse the environmental consequences of land management and to help frame land management policies that might mitigate them, it is doubly important that model results are correct. Such policies often involve trade-offs between profitability and

environmental benefits, and the balance may or may not benefit the land manager initiating change in land management.

There are several ways to verify a model and it is wise to use as many of them as possible.

Direct comparison of model output with measured data

Direct comparison of model output with measured data might be done for individual locations within (or at least close to) the survey region where there are measurement parameters predicted by the model. Such sites include agronomic experiments, field trials in farmers' fields, and forestry trials where there is the necessary instrumentation for regular measurement of the necessary parameters (preferably over several years). The comparison should include calculation of statistics such as r^2 (the proportion of variance in the measured data accounted for by the model predictions), root mean square (RMS) residual (the average size of the errors) and mean residual (showing whether the model is systematically overpredicting or underpredicting). Thomas et al. (1995) and Paydar et al. (1999) compared crop and water balance parameters predicted by the PERFECT and APSIM crop models with data from an agronomic experiment in the region where it was to be used. Similarly, Tickle et al. (2001) validated productivity predictions by a forest model, 3PG-SPATIAL, against 12 forest plots over a survey area of 500 km².

Remotely sensed data

Model results for a region can also be compared to remotely sensed data. For example, predictions of leaf area index by a model can be compared to the Normalised difference vegetation index (NDVI) calculated from satellite data at regular intervals (see *Chapters 11 and 12*). An advantage of this method is that, while only a single output parameter is compared, it allows comparison for many more locations or whole areas, as well as checking the relative difference between locations. Satellite data are also relatively cheap to obtain, and often cover many more years than do data from most experimental sites.

Integrating or emerging properties

Where models are predicting the behaviour of whole areas, such as catchments, it is useful to verify not only that the model is correct at individual locations but also that the emergent attributes of the catchment as a whole, such as stream flow or groundwater levels, are correct. This requires checking against data from stream-gauging stations or piezometers.

Critical review

A less formal way to verify model output is through seeking critical comment of interim results by stakeholders, who have local knowledge of at least some of the parameters predicted by the model. It can be useful to consult both land managers, such as farmers or foresters, who know behaviour of their land intimately, and local experts, such as district agronomists, who have a more general knowledge of behaviour for a whole district. Involvement of such stakeholders early in a project not only helps ensure the model is giving believable answers, but also gives stakeholders a sense of ownership which aids later implementation of recommendations from the project.

Use as many of the above methods for verification as possible because they are in large measure complementary.

Conclusions

Combining simulation modelling and land resource survey has the potential to provide powerful tools for developing systems of land use that are both profitable and environmentally

benign. Simulation modelling allows data from surveys to be applied in sophisticated ways that consider multiple components of the system. Similarly, the data are essential for applying such models across large regions. However, to be effective, land resource surveys have to provide primary data relating to the storage and movement of water, nutrients, solutes and sediments.

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Intensive survey for agricultural management

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Introduction

Demand for reliable soil information across the agricultural regions of Australia is increasing. Declining terms of trade and intense competition are forcing land users to review all aspects of their enterprises. Most effort has been devoted to improving crop varieties, optimising fertiliser strategies and controlling diseases. Much greater attention is now being directed towards soil constraints to production, and this requires a capacity to measure and map these constraints; the counterpart is an effort to develop strategies for soil amelioration and monitoring. Other factors increasing the demand for soil information include legislation on water use in agriculture, ambitious targets for catchment management across most agricultural lands, and the emergence of Environment Management Systems to meet demands from the market.

Therefore, surveys that address the issues listed above focus on the constraining soil attributes and tend to quantify variation in fewer landscape features than is the case for natural resource surveys or land system surveys. Generally, professional soil scientists are asked to assess the suitability of the soil in fairly small areas for a single land use. Consider as an example grape production with drip irrigation optimised for partial root-zone drying. The capacity of the soil to accept and store water will have a large impact on management, and so survey should focus on hydrological properties of the soil, though a surveyor will check to see if other properties such as salinity, pH, structural condition and nutrition require modification. In soil surveys for citrus crops, the depth to clay-rich layers with high pH is likely to be critical. This targeted approach – with its emphasis on key soil factors – may be regarded as a ‘Critical Factors System’.

Soil variation within management units can have a major effect on farm performance. For example, Bramley and Profitt (1999) show that annual gross margin for wine-grape production within a Coonawarra vineyard ranged from a loss to a A\$12,000 profit per hectare. Wide variations such as these are almost always caused by soil. Poor crop yields also tend to be associated with environmental problems associated with excessive deep drainage (e.g. salinity, eutrophication of waterways).

The demand for soil information is most evident in the following agricultural industries:

- irrigated horticulture and viticulture with both pressurised and non-pressurised irrigation
- cotton and sugar with furrow irrigation
- rice and pasture with bay irrigation
- vegetables with centre-pivot and lateral-move irrigation systems
- dryland grain

- dryland pasture
- agroforestry plantations.

In most instances, land users aim to maximise profits by balancing inputs (e.g. fertilisers, ameliorants, fuel, irrigation water) against crop yield and quality. In conjunction with catchment managers, they also aim to:

- control secondary salinisation, caused by excessive deep drainage, in conjunction with an impeding layer, and a lack of leaching when using poor quality irrigation water
- maximise carbon accumulation, and minimise the release of 'greenhouse gases' from the soil
- prevent contamination by chemicals
- regulate chemical, physical and biological properties of the soil to ensure a 'healthy' landscape and production system for the future.

Most users of rural land in Australia are busy people, and they receive a continuing barrage of information relating to their operations. They are usually keen observers of their land and are averse to unnecessary expenditure and risk. Therefore, to be effective, soil information (e.g. maps, reports) must take into account the landholder's observations and be:

- concise but comprehensive
- as accurate as possible (defensible in a court of law)
- clearly presented with a minimum of jargon
- available in convenient formats; for example, written reports with a set of scaled (1:500–1:10 000) colour-coded maps, preferably with digital information for a geographical information system (GIS), and supplemented by photographs of the development site and representative soil profiles
- not be too expensive.

This chapter reviews the common methods for providing advice on soil management in a spatially explicit form. It focuses on methods used by the commercial advisors in soil survey. The methods are pragmatic and reflect commercial reality. Although most soil surveyors in the private sector readily adopt new technology, such technology has to improve survey efficiency and reduce risk for the land user.

There are three main circumstances within which commercial soil surveys are conducted, as follows.

- 1 Preliminary assessments. These are used by investors to determine whether they should proceed with the purchase and development of land for their intended land use. Poor choices can lead to expensive failures or remediation. For example, failure to recognise the presence of intractable heavy clay subsoil (with large amounts of active free lime) close to the soil surface in a citrus development is likely to lead to serious financial losses for the developer because of poor yields (Cockroft and Dillon 2004). The accredited 'expert opinion' of the land evaluator is important in this decision-making process.
- 2 Detailed assessments for new agricultural developments.
- 3 Monitoring and 'trouble shooting' in existing agricultural enterprises (Rasic 2005).

Sampling

Most intensive soil surveys for new agricultural developments in Australia rely on grid sampling and inspections of pits. Grid sampling is favoured because the landscapes are fairly flat, and

stratification according to landscape features such as landform is not straightforward. Grids also provide an even spread of observations across the land. Several variants on grid sampling are discussed (see *Grid sampling*).

An alternative approach is to use maps made from electromagnetic induction (EM surveys – see *Chapter 17*) to define where the soil should be sampled. However, this almost certainly will introduce major errors in at least some of the maps of soil factors on which a comprehensive assessment is required. This is because the spatial patterns of variation of each of the relevant ‘key soil factors’ (e.g. pH, compaction severity, depth to lime, clay content, water holding capacity, dispersion, salinity, nutrients) almost never coincide at any particular site. So, although the EM data correlate strongly with, say, subsoil salinity, the same EM data might be unrelated to some of the other critical soil factors that relate to crop production and so not be useful in that regard.

If the main aim of the soil survey is to assess salinity, or properties strongly correlated with salt content (e.g. deep drainage assessment under rice bays), then we can use the EM map to define soil sampling sites.

Assessments of existing farms will include information on crop yield and management in previous years. Interview farm staff familiar with the property over a long time and ask about yield and management in very wet and very dry seasons. Where possible, obtain yield data and rank paddocks from worst to best. Select paddocks that, on average, have the worst, median and best performances. Split these into regions of poor, mid-range and good yield based on visual estimates or, if available, on yield maps generated by Global Positioning Systems (GPS)-guided harvesters. At each of the nine points thus identified, dig inspection pits to a depth of 1.5 m with a backhoe to assess the soil condition comprehensively (see *Soil inspection methods*). These pits form the foundation. If required, follow up by investigating just a few key factors (e.g. sodicity, pH) at extra sampling sites.

Grid sampling

In the Australian horticultural and wine industries the ‘standard’ sampling intensity for new developments usually is either one pit per hectare on flat land (100 m grid spacing) or more (usually 75 m) on hilly land. Closer spacings are needed in landscapes with large variation of short range, particularly where effluent water is used. Broad-acre developments tend to have an adjustable grid spacing of 200 m to 500 m. Once the pits on the adjustable grid have been dug, extra georeferenced pits may be excavated where important additional variation (e.g. in sand-dune and swale country, regions with gilgai micro-relief) needs to be considered. The GPS-derived elevation maps produced by some remote sensing contractors can help to locate additional soil pits.

Maps are usually prepared at a scale of 1:1500, but may be as detailed as 1:500. The least detailed scale for detailed soil survey is about 1:10 000.

Benefits of grid surveys include the following.

- It is a simple, standard system that is practicable and easily understood by all involved – surveyors who peg pits, backhoe operators who dig them, cartographers who make maps, end-users who interpret them.
- It is almost automatic to step into the pit, describe, climb out and move to the next one along transect, get to the end, move along one transect and come back. Clients get good value as more pits can be described per hour than if surveyors have to probe before choosing where to dig.
- Once all the pits have been described, the surveyor returns to a representative subset of the profiles to sample and photograph the soil. Unrepresentative anomalous sites such as the remains of old tree roots are avoided when sampling. Clients can be taken on a tour of the pit sites to help them visualise their soil resource.

- It is easier to fit statistical surfaces to data from grid surveys than from irregularly scattered observations.
- A prior knowledge of soil distribution is not essential. This means that the bias caused by preconceived ideas is minimised.

There are some disadvantages, including the following.

- Strict adherence to the grid means that fairly uniform land is likely to be sampled unnecessarily densely and more heterogeneous land too sparsely. It takes no account of the relative risks of using and managing land. For example, patches of land where salinity is likely to develop or where the soil is already somewhat saline merit more intense sampling than elsewhere.
- Prior knowledge about soil variation in the landscape counts for nothing, and so there is a tendency for practitioners undertaking grid surveys to disregard this source of information.

To guarantee a cost-effective outcome for clients, land evaluators have to ensure that the nominated pit spacings suit the proposed land use and the type of land. Their documented expert opinion will also be needed to choose the best mix of measurement techniques for each new study.

Soil inspection methods

The digging equipment selected depends upon the size and complexity of survey. Options include backhoes, corers and augers (see *Chapter 16* for the pros and cons of each).

Backhoe pits are preferred because they reveal clear pictures of the soil profile. In particular, they reveal impeding layers and root patterns. You should remove smeared or compressed soil from the pit face with a geological pick to see them to best advantage. If you discover a plough pan, trim back overlying loose soil and the underlying uncompacted soil to create a protruding damaged layer that is easy to describe (Trowse 1983).

Obtain digital images to create a permanent record of the main morphological features. Associated root growth can be highlighted, if required, with white paint (Myburgh et al. 1998). Bear in mind the cliché that ‘a picture is worth a thousand words’ when presenting soil information to a client.

Pits deeper than 1.5 m require shoring (see *Chapter 16*), but 1.5 m is deep enough to include the root zone of most agricultural crops. For crops with shallower rooting systems (e.g. vegetables, some types of citrus), a depth of 1.2 m is adequate usually. Backhoes and excavators with a bucket width of at least 0.60 m are the favoured machines. Almost all rural areas in Australia have contractors with such equipment.

Some pits (about 1 in 10) should be dug to 3.5 m (with shoring) or to rock (Cockroft and Dillon 2004), with inspection of the deep drainage characteristics and salinity status of the excavated material beside the pit.

For tree crops, such as pecans, that have roots extending to a depth of over 5 m, a combination of pits (1.5-m deep) and cores (6-m deep) should be used.

Where there is emphasis on near-surface soil properties, pits to 0.4 m deep can be dug with a spade to obtain extra information in between the deeper pits (Munkholm 2000; McGarry and Sharp 2001).

Cores can be used instead of pits, although they are of limited value for soil structural assessment if their diameter is < 75–100 mm (McIntyre 1974), and the corers are difficult to insert in soil containing many coarse fragments. Nevertheless, cores are often used on sandy sites with broad-acre pivot irrigation. In-filled backhoe pits can create low spots, which may

impede movement of the wheels of a travelling irrigator. It is possible, however, to overcome this problem by compacting the soil as you replace it and then scraping a little extra soil from the surrounds and placing it on top of the original pit.

Augers are of even less value than corers because the soil's structure and fabric are destroyed during sampling.

Incorporating prior information

Prior information on landform and geology (e.g. May 2002; Hulme 2003) and previous land use should be accessed to help plan sampling. Refer to databases such as ASRIS (2006) to determine what soil data already exist for a region. Where native vegetation has not been fully cleared, its characteristics can provide valuable clues about soil properties.

Options for measurement

Intensive surveys for agriculture tend to measure fewer soil properties than less detailed surveys. The selected properties are specific for the aims of the survey, which generally relate variation in management to predicting variation in crop performance across a site. As a result, the major differences between intensive and general purpose surveys at broader scales are:

- a greater proportion of resources is devoted to laboratory analysis (Rayment and Higginson 1992) and detailed assessment of soil physical properties (McKenzie et al. 2002)
- more reliance on visual–tactile assessment of key soil factors in pits including soil structure, water-holding capacity and evidence of waterlogging ('functional morphology')
- ground-based remote sensing to supplement the observations from pits, notably electromagnetic induction
- results from monitoring soil water and the performance of crops guides subsequent sampling, measurement and diagnosis.

Soil problems such as compaction, acidity, salinity, dispersion and nutrient deficiency can greatly reduce the efficiency of water use and profitability of cropping. Therefore, identify soil characteristics that restrict crop growth and devise cost-effective strategies for amelioration (seek advice from agronomists, horticulturalists, viticulturalists and foresters where necessary).

Assess soil condition to the expected maximum depth of root penetration for the land use under consideration. Relevant soil qualities include:

- water intake and storage capacity (influenced by texture, coarse fragment content, severity of compaction and development of pans, slaking, dispersion, shrinkage and swelling, and organic matter content)
- water-logging hazard (slaking, dispersion, severity of compaction and development of pans, flat or low-gradient land, gilgai micro-relief, and pathways for lateral flows of water in the subsoil, above impermeable parent material and from upslope)
- excessive hardness for root penetration, or seedling emergence, or both, caused by slaking and hard-setting (Mullins et al. 1990) or applied compactive and smearing forces
- excessive hardness for root penetration caused by concretions
- risk of excessive deep drainage
- presence of harmful salt
- soil pH imbalance (acidity, particularly in acid sulfate soil, and alkalinity with associated carbonate accumulation)
- nutrient deficiencies or accumulations (in topsoil, in deep subsoil)
- erosion hazard

- a bearing capacity that can sustain mechanised farming and trampling while maintaining open porosity for unrestricted root growth and water penetration.
- water repellence (mainly in sands, but possible in clay-rich soil)
- soil biological health (where suitable tests exist)
- toxic pesticide residues.

It is not necessary to fully assess all of these soil factors on all occasions. For example, it is pointless when using a 'Critical Factors System' to assess shrink-swell in an area dominated by sandy soil, or to measure active carbonate content at a soil that obviously is acidic. However, commercial soil surveyors have a responsibility to the administrators of state and national databases, who have protocols and minimum standards for data collection associated with land evaluation. Therefore, some of the morphological data recorded will be less relevant than the critically important factors associated with the immediate aims of the soil assessment.

Field diagnosis using visual–tactile assessment

There are several schemes for visual–tactile assessment of soil exposed in pits. These augment schemes for conventional soil morphology (e.g. McDonald et al. 1990). They emphasise the detection of various impeding layers that restrict root growth or movement of water, particularly hard zones. Also, there are rapid procedures for the prediction of soil water-holding capacity (based on the field assessment of soil texture, soil structure and coarse fragment content) and risk of waterlogging (from features such as subsoil colour and mottling patterns). The schemes are often applicable to a specific range of soil types or a particular farming system. Here we describe several systems for visual–tactile assessment that have proved useful for irrigated agriculture in Australia.

Soil structure assessment

SOILpak

SOILpak is a Decision Support System for the assessment and management of soil quality. It was designed originally to assess compaction under irrigated cotton on Vertosols (Daniells et al. 1996; McKenzie 1998). It is now applicable to a wide range of soil types and cropping systems (Anderson et al. 1999).

The soil structure section of SOILpak considers the following features, as defined by Kay (1990):

- structural form
- structural stability in water (severity of slaking and dispersion)
- structural resilience (potential for loosening of compacted layers by natural processes such as shrinking and swelling and biological activity).

The SOILpak score (McKenzie 2001a,b) relates to soil structural form (the severity of compaction). It is derived from European and British methods described by Batey (1988; 2000). The key consideration is root growth. The SOILpak scoring procedure is linked to aeration, and also to strength limitations that are summarised within the framework of non-limiting water range (McKenzie and McBratney 2001).

The upper 0.9 m of the root zone is assessed after the pit face has been picked back to remove soil disturbed by the bucket of the excavator. The target depths are: 0–0.1 m, 0.1–0.3 m, 0.3–0.6 m and 0.6–0.9 m. A cube of soil 70 mm × 70 mm × 70 mm is evaluated from the centre of each of these depth intervals.

Where controlled-traffic and raised-bed farming is practised, the assessment zones are under the bed next to the main wheel track, and under a bed away from a main wheel track.

Where the traffic patterns are haphazard, the scoring is done under both the worst (under wheel) and best (interwheel) sections of the trimmed faces of pits, and these are oriented at right angles to the main direction of machinery movement.

The SOILpak score ranges from 0.0–2.0. Beginners can start with a three-point (0, 1, 2) scale, inexperienced users a five-point (0.0, 0.5, 1.0, 1.5, 2.0) scale, and experienced operators a 21-point (0.1, 0.2, 0.3 ... 1.9, 2.0) scale. The clod and aggregate factors taken into account are:

- size after applying moderate hand pressure
- resistance to deformation
- shape
- clods within clods (related to soil friability)
- internal porosity of the smallest observable clods.

There is a weighted averaging procedure (McKenzie 1998; 2001a) that can be applied where the scores for the various factors do not agree. Override factors are used in the following circumstances:

- 1 presence of interconnected vertical macropores (at least 2 obvious macropores in the 70 mm cube) – add 0.5 to the SOILpak score if it is less than 1.5. If possible, highlight the macropores with a mixture of white paint (1 part) to water (7 parts)
- 2 presence of a thin smeared layer (often with associated anaerobism) within the depth interval under consideration (if the score is above 0.5, down-grade it to 0.5)
- 3 crusts (where there is a surface crust or hard-set layer with a thickness greater than 5 mm, downgrade the SOILpak score of the topsoil to 1.0 if the score is greater than 1.0).

The SOILpak score is linked to land management as follows.

- ▶ A score < 0.5 indicates serious compaction. Compaction in this context includes both mechanically compressed soil and cemented layers. Soil loosening (e.g. chisel ploughing) at a water content just less than the plastic limit is essential for healthy root growth.
- ▶ A score in the range 0.5 to 1.5 is associated with moderate compaction. Soil loosening, carried out either mechanically or biologically, is desirable.
- ▶ A score > 1.5 is considered to be excellent. The soil need not be loosened.

The ASWAT test (Field et al. 1997) is used to assess clay dispersion. Values > 6 (on a scale 0–16) indicate a need for gypsum (or lime, or both, depending on soil pH) and organic matter. Scores from 2–6 indicate that you should not work the soil when it is moist. The ASWAT test is an abbreviated version of the dispersion index described by Loveday and Pyle (1973). These authors showed that where that dispersion index exceeded 8 (equivalent to an ASWAT score of 6), soil hydraulic conductivity was invariably < 1 mm/hour, at which soil requires improvement for successful irrigated agriculture. Selected specimens are analysed in the laboratory for exchangeable sodium percentage, calcium:magnesium ratio and electrochemical stability index (McKenzie 1998) so that the processes associated with any dispersion can be understood.

Other visual–tactile structure assessment schemes

Visual soil assessment (VSA) (Shepherd 2000) was developed in New Zealand to provide land managers (regulatory authorities, consultants, farmers) with a simple and standardised method to assess and monitor soil quality quickly and cheaply on both arable land and grassland. It is based on the manipulation of a spadeful of soil from the topsoil and, if desired, from lower horizons to examine the subsoil. Key criteria are the identification and sorting of aggregates by size, shape and abundance, aggregate porosity, colour, mottles, erosion and earthworm count. Eight indicators are assessed on a scale from 0 to 2.0 by comparison with

photographs in a field guide. An undisturbed reference specimen is taken from under a fence or native vegetation nearby.

Several other useful visual–tactile schemes for assessing soil structure have been developed. They are described by Munkholm (2000), Boizard et al. (2002), National Soil Resources Institute (2002) and Ball and Douglas (2003).

Estimation of soil water holding capacity

Option 1: ICMS–Wetherby

Research at Loxton, South Australia, in the 1980s determined water retention curves for a range of moisture deficits on a variety of soil types with a broad range of particle-size distributions (Wetherby 2003). These data were then correlated with field texture (Table 29.1). The resulting pedotransfer function allowed mapping of readily available waterholding capacity (RAW) rather than morphological soil type, series, and family.

RAW values for the potential rooting zone at a selected moisture deficit are calculated first by multiplication of the thickness of each layer (cm) within the root zone by the RAW conversion factors (Table 29.1) for the field texture of that layer. The RAW values calculated for each layer within the expected root zone are then summed. The values for each layer within the potential root zone are reduced by the respective percentage where coarse fragments (gravel, rock) are present. Maps of RAW and the associated soil survey data are used by irrigation designers to assist with definition of the boundaries of irrigation management units (IMUs) (Sparrow and Norton 2004).

The introduction of this system greatly improved the efficiency with which irrigation water can be used in south-eastern Australia. Nevertheless, further improvements on the ICMS–Wetherby methods have been suggested. For example, Rius (2004) has highlighted the need to be able to predict potential rooting depth – and the associated RAW values – following amelioration of soil at a new development site, rather than just for the unimproved soil at the time of sampling.

Table 29.1 Available waterholding capacity (mm of water per cm of soil) of various field textures at 5 deficit ranges (Wetherby 2003)

Texture grade	–8 to –20 kPa	–8 to –40 kPa	–8 to –60 kPa	–8 to –200 kPa	–8 to –1500 kPa
Sand	0.33	0.36	0.37	0.46	0.62
Loamy sand	0.45	0.52	0.55	0.65	0.86
Clayey sand	–	0.55	0.60	0.74	1.01
Sandy loam	0.46	0.59	0.64	0.84	1.15
Light sandy clay loam	0.45	0.65	0.74	1.03	1.37
Loam	–	0.69	0.84	1.00	2.34
Sandy clay loam	0.39	0.61	0.71	1.03	1.43
Clay loam	0.31	0.53	0.65	0.90	1.18
Clay	0.27	0.46	0.57	0.49	1.49
Heavy clay	–	0.25	0.41		1.20

The clayey sand values are interpolated. The heavy clay sample was from Kununurra, WA.

Option 2: Modified WA Soilguide

A combination of the systems of Moore et al. (1998) and Wetherby (2003) can also be used to estimate available water in the soil. The conversion factors are listed in Table 29.2. This scheme takes into account field texture, particle size of the sand fraction and soil structural form.

It is assumed that following implementation of a soil management plan at a site, soil structural form will be favourable for root growth and water movement after amelioration. Therefore, maximum conversion values from the ‘weakly structured or apedal’ soil structure column of Moore et al. (1998) (Table 29.3) are used for sand, loamy sand and clayey sand. Averages of the ‘moderate–strong structure’ values are used for the remaining texture groups. The RAW (–8 to –60 kPa) values were predicted from the total available water (TAW) (–8 to –1500 kPa) data of Wetherby (2003).

Where a crop’s rooting depth cannot be predicted with any confidence, RAW values are calculated for thicknesses 0 m to 0.5 m, 0 m to 1.0 m and 0 m to 1.5 m. Once rooting depths have been determined at a particular site from water extraction patterns (e.g. neutron probes and capacitance probes, see Charlesworth 2005), the thickness component of the RAW can be refined.

The RAW values for each horizon are adjusted – where appropriate – according to the content of coarse fragments. If one suspects that the coarse fragments are porous and able to store significant amounts of water, then sample the soil and measure their pore space relations and make adjustments according to Cresswell and Hamilton (2002).

Where it is not economically feasible to optimise soil structural form, Table 29.3 can be used to adjust RAW and TAW values according to the severity of compaction evident in the soil. The

Table 29.2: Readily available water (RAW) (–8 to –60 kPa) and total available water (TAW) (–8 to –1500 kPa) conversion factors (mm/cm) for the ‘Modified WA Soilguide’ scheme: Option 2A; Post amelioration, with soil structural form close to ideal.

Texture	Particle size of the sand fraction	–8 to –1500 kPa (Pasture)	–8 to –60 kPa (Grapevines)
Sand	Coarse to very coarse	0.20	0.18
	Medium to coarse	0.45	0.40
	Medium	0.50	0.42
	Fine	0.70	0.46
Loamy/clayey sand	Coarse	0.60	0.44
	Medium	0.90	0.51
	Fine	1.00	0.53
Sandy loam	Coarse	1.65	0.69
	Medium	1.40	0.63
	Fine	1.95	0.76
Light sandy clay loam	Coarse	1.35	0.61
	Medium	1.95	0.76
	Fine	1.80	0.72
Loam	–	1.95	0.76
Sandy clay loam	–	1.60	0.68
Clay loam	–	1.65	0.69
Sandy clay	–	1.40	0.63
Clay	–	1.15	0.57
Clay (self mulching)	–	2.10	0.79

Table 29.3 Estimating total available water (TAW) from soil texture, particle size of the sand fraction and structure (Moore et al. 1998): Option 2B; Includes situations where structural form is not ideal.

Texture	Clay (%)	Sand fraction	Available Water Capacity (mm/m)	
			Moderate to strong structure	Weakly structured or apedal
Sand	<5	Coarse to very coarse	–	~20
		Medium to coarse	–	30–45
		Medium	–	40–50
		Fine	–	50–70
Loamy sand/ clayey sand	5–10	Coarse	–	50–60
		Medium	–	60–90
		Fine	–	80–100
Sandy loam	15–20	Coarse	110–220	50–60
		Medium	110–170	60–100
		Fine	170–220	~140
Light sandy clay loam	15–20	Coarse	120–150	50–60
		Medium	170–220	90–100
		Fine	~180	100–120
Loam	~25	–	150–240	100–130
Sandy clay loam	20–30	–	130–190	100–130
Clay loam	30–35	–	120–210	~100
Sandy clay	35–40	–	130–150	80–100
Clay	>35	–	110–120	90–140
Clay (self-mulching)	>35	–	~210	–

‘moderate–strong’ structure corresponds to a SOILpak score of >1. ‘Weakly structured or apedal’ structure corresponds to a SOILpak score of <1.

When assessing texture by hand in the field, be aware of the danger of underestimating clay content in subplastic soil (Butler 1955; McIntyre 1976; McDonald et al. 1990). Obtain particle-size analysis on a subset of soil specimens selected for laboratory analysis. In saline soil, the osmotic effect on plant available water should be taken into account.

Evidence of recent waterlogging

The roots of most crops grow poorly when the soil is waterlogged (except for rice). The lack of oxygen for root respiration usually is associated with other undesirable processes such as conversion of nitrate-N to nitrous oxide. Under severe reducing conditions, sulfates are converted to foul-smelling hydrogen sulfide.

Anoxic conditions in soil create redoximorphic features. The anoxic conditions may be permanent or occur only occasionally. Signs of waterlogging in soil include the following (see *Chapter 7* and Batey 1988, 2000):

- yellow and grey colours
- mottled colour patterns, caused by changes in the distribution, concentration and state of oxidation of iron compounds
- transport and re-precipitation of manganese compounds to produce manganese oxide nodules.

Bleached horizons can indicate that iron compounds have been made more soluble by reduced conditions and then leached. These components may precipitate as placic (thin ironpan) horizons (20–30 mm thick bands of sand cemented by complex mixtures of iron, manganese, aluminium and organic compounds; wavy and strongly indurated) (Duchaufour 1998).

It is difficult to distinguish contemporary mottles produced by current conditions and site management from relict mottles.

The production of maps showing 'depth to layer showing evidence of recent waterlogging' forms the basis of a site drainage plan.

In soil that appears to have favourable aeration status in dry regions, mottling and gleying can quickly develop under irrigation where impeding layers such as pans restrict permeability.

Ground-based remote sensing

Several systems for ground-based remote sensing are now used routinely for intensive surveys in agriculture. Most significant is EM (see *Chapter 17*, Spies and Woodgate 2005). Contractors normally provide maps of the EC_a (bulk electrical conductivity) of soil within and below the root zone. The technology is used in conjunction with GPS to provide detailed maps of individual paddocks. The depth of measurement ranges from about 1 m to 2 m (EM-38) to 40 m to 50 m (EM-34). The EM-31 device measures EC_a to a depth of about 5 m to 6 m.

On the Riverine Plains of New South Wales and Victoria, EM survey is often used for estimating the potential for deep drainage – 'leaky' soil tends to have small EC_a . In some regions, maps of EC_a are useful for predicting the soil's water holding capacity. This correlation arises because, in semi-arid environments, the electrical conductivity often increases at the base of the root zone (McCown et al. 1976), and soils with a shallow root zone often have a larger EC_a detectable via an EM-38 or EM-31.

Various configurations of materials with differing dielectric properties can produce a similar EC_a . For this reason, calibration is always necessary at new locations. This applies to other methods for ground-based remote sensing such as gamma-ray spectrometry (see *Chapter 13*) and airborne or satellite-based remote sensing (see *Chapters 11 and 12*).

The main benefits of remote sensing for intensive surveys are to provide extra information for empirical stratification for sampling and to give covariates to assist with mapping. The quality of mapping will always rely heavily on the quality of the primary soil measurements – via a network of pits – and the strength of their correlations with surrogates used for inference in between the pits.

Rapid soil measurement with new sensors

The proportion of pits sampled for soil analysis in the laboratory generally is in the range 1/3 to 1/5, but this proportion is likely to decrease when cheap techniques such as mid-infrared spectroscopy (MIR) (see *Chapter 17*, Janik et al. 1998) are introduced.

If it becomes possible to measure accurately a comprehensive set of topsoil and subsoil attributes 'on the go' with arrays of sensors mounted on GPS-guided farm machinery (ACPA 2006), then soil surveys will become rich in data. The procedure would allow thorough interpretation of maps of crop yield and quality, and variable-rate soil amelioration maps would become more accurate. A more likely outcome for rapid data acquisition, at least in the near future, is the development of MIR scanners for the rapid characterisation of soil chemical properties on the carefully trimmed faces of pits and large cores.

Soil scientists will continue to examine the soil in pits and develop their skills, which are unlikely ever to be completely superseded.

Information gained by modern methods and associated terrain information are likely to become increasingly useful as input to process-based models of soil quality and crop production for both farming and catchment management.

Many of the new systems for rapid soil measurement (see *Chapter 17*) are being developed in response to the demands of precision agriculture, which many managers are keen to adopt. Precision agriculture can be implemented via the use of variable rate technologies in at least two important ways:

- 1 permanent zone management using zones based largely on difficult-to-alter attributes such as depth to bedrock and major texture differences
- 2 transient zone management using zones that change according to easily adjusted soil qualities – e.g. dispersibility, compaction severity, pH, season.

An example of the practical application of precision agriculture techniques in dryland farming is presented later (see *Interpreting yield maps and managing zones*).

Mapping

Mapping in intensive survey for agriculture is nearly always a matter of expert judgement. The following lines of evidence are used to delineate management zones:

- direct interpolation for each soil variable measured in pits
- remote sensing (air photographs and satellite images)
- ground-based remote sensing, in particular, electromagnetic induction.

Maps of the soil qualities are prepared. These can be colour-coded with red or orange hues to designate problem zones and green or blue colours for satisfactory conditions. This approach highlights zones that require special treatment. Following ameliorative treatments in response to such information, some of the soil quality maps will have to be reviewed and updated as part of an on-going program.

Convenient depth intervals for the mapping are the same as those for description: 0 m to 0.1 m (topsoil), 0.1 m to 0.3 m (subsurface), 0.3 m to 0.6 m (upper subsoil), and 0.6 m to 0.9 m (mid subsoil). Soil evaluations that examine only the topsoil are of little value – the roots of most agricultural crops extend much deeper into the subsoil.

The use of full colour on maps to show estimated soil conditions in between sampling points can give a false impression about the accuracy of the maps. Therefore, colour-coded circles can be used to designate soil condition at each sampling point on a map, and the zones between the sampling sites may be left blank to show clients that the knowledge of soil over their properties remains incomplete. Specimens from each point should be kept separate (i.e. not bulked) to provide the data for these maps.

The maps of soil qualities can, if required, be converted to maps of proposed soil amelioration and cost of repair (McKenzie 2003). The ability of land managers to restore damaged or degraded soil becomes more economically attractive as the value of a crop increases. The ‘cost of repair’ maps have a similar intent to maps of ‘soil limitation and suitability’ described in the following list which summarises four broad types of maps considered useful for applications in agriculture.

- 1 *Soil type map*. All available soil information for the region is integrated to generate a soil type map (base map). This map on its own is seldom adequate for irrigation planning and decision-making – only rarely can it distinguish between areas that have contrasting limitations, suitability, amelioration or irrigation management needs. Even so, the base map is important, as it is from this map containing all the available data that one derives a series of interpretive maps showing characteristics that are critical for the specified land uses.
- 2 *Soil limitations and suitability map*. The site-specific soil properties that are critical for the intended use are identified. Various soils can then be grouped into classes called suitability units, which have one or more specific but similar limitations where the degree or severity

of limitations is the key determinant for the particular land use. Each suitability unit can comprise a wide range of contrasting soils, all of which require similar corrective measures for their improvement.

- 3 *Soil amelioration map.* This explains how the specific limitations shown on the suitability map can be overcome. The soils that have similar problems, and therefore similar amelioration requirements, are grouped in amelioration units. Not all of the contrasting soils grouped together in an amelioration unit are expected to have identical amelioration needs, but the needs of the dominant soil type must apply to all of the soil types included in a group. In complex landscapes, the dissimilarities are usually such that pockets of disparate soils will respond differently to the same management, even after corrective measures have been implemented.
- 4 *Soil potential map.* The fourth and final step is to produce a 'soil potential' map to predict the soil status after amelioration. This map is derived mainly from the 'amelioration' map and is designed to group the ameliorated soils, according to their production potentials into irrigation management units. This process is used on the assumption that the recommended soil improvement will be followed, and that irrigation management methods will be adjusted to match the ameliorated soil.

Sparrow and Norton (2004) show how maps of 'soil profile description', 'depth of topsoil' and 'readily available water' – derived using an alternative system described by Wetherby (2003) – are used to prepare a plan of irrigation scheduling units.

Interpretation for optimal management of soil and crops

Soil assessment needs to start with the requirements and potential rooting depths of the crops under consideration for the farm. Critical limits for key soil factors vary between species (Landon 1984) and Liebig's 'Law of the Minimum' provides a useful starting point (Hackett 1988). It suggests that only when all limitations are removed simultaneously does plant production have a chance of reaching its biological potential.

Nevertheless, a commercial soil surveyor needs to be able to recognise which characteristics are likely to be the most important at a specific site for a nominated outcome. He or she can plan the survey accordingly. For example, a soil survey to assess site suitability for citrus will pay special attention to the depth to free lime and clay content. Extra pits may have to be dug to assess quickly only these factors.

Certain publications provide valuable information and helpful guides to interpretation, but none give comprehensive information to support decisions on soil assessment and management for a broad range of soil types and land uses. The most useful, in our opinion, are the following: Davies et al. (1972), Landon (1984), Batey (1988), Hunt and Gilkes (1992), Freebairn et al. (1997), Moore (1998), McKenzie (1998), Cornforth (1998), Anderson et al. (1999), Peverill et al. (1999), Glendinning (1999) and Nicholas (2004).

Several state government departments and private companies have developed soil assessment and management 'packages' that can be used commercially for intensive agricultural developments. Most of these systems are continuing to evolve. Some components of these systems are discussed in the next three sections: *Irrigation design*, *Monitoring and adaptive management* and *Interpreting yield maps and managing zones*.

Irrigation design

Irrigation assessment is a large topic in its own right. Irrigation requires major investments in infrastructure – dams, channels, land levelling or grading equipment, and water itself costs money. The soil must be good enough to justify the expenditure, and variation in soil that

requires variation in management needs to be recognised and mapped. Soil survey is nowhere more important. When dealing with new irrigation developments, pay close attention to soil hydraulic properties, requirements for soil amelioration and monitoring.

Soil hydraulic properties

Soil hydraulic properties (infiltration and permeability, water holding capacity, drainage) are critical. This is particularly so when pressurised irrigation systems are used – everything possible is done to ensure that both the design and operation of systems for irrigation are matched to the soil.

Options for measurement describes how readily available water (RAW) can be estimated, with and without soil amelioration. Maps of RAW following amelioration are particularly useful for the definition of irrigation management units. They show where soil cannot be modified in a cost-effective manner (e.g. shallow stony soil), and where separate control valves are needed for irrigation in small amounts at frequent intervals (Sparrow and Norton 2004).

Where permeable soil overlies impermeable rock on sloping land in wet climates, the lower-lying land is likely to receive drainage and runoff water from upslope. In irrigated orchards and vineyards, this process is most evident in early spring following a wet winter. To minimise the risk of overwatering the downslope areas, the manager should install a separate control valve for irrigation, even if the RAW values for the upslope and downslope zones are similar.

Surveyors should try to assess the degree to which water will move laterally from the point of wetting. Battam et al. (2000) describe how a combination of watering from a range of drip irrigation emitters and mini-pits can be used to determine empirically the wetting patterns in topsoil *in situ*. Where the topsoil is susceptible to slaking and hardsetting, this method of testing is attractive and informative.

If required, a drainage system should also be designed for the site. An excess of water is no less serious than a drought stress induced by lack of water.

The expected hydraulic conductivities for a broad range of textures, structural conditions and salinities have been presented by Geeves et al. (2000). If the client is willing to pay for the extra service, direct and more accurate measurements of soil hydraulic properties can be made by techniques described by McKenzie et al. (2002).

Soil amelioration and damage prevention

Land evaluators supply their clients with plans that describe the required sequence of amelioration procedures and on to minimise the risk of soil degradation. They state the potential of the land after corrective measures have been implemented.

The outcomes of soil amelioration can be impressive. Cockroft and Tisdall (1978) described how irrigated peach yields on a troublesome Sodosol were quadrupled through a combination of deep ripping, applications of gypsum and organic matter, mounding, mulching and spray irrigation.

Management options to consider (with recommended references) within a comprehensive soil management plan include the following:

- deep loosening (biological or mechanical via tillage or both) to overcome compaction limitations (Buckingham and Pauli 1993; McKenzie 1998; Spoor 2006)
- deep mouldboard ploughing to increase the surface clay content of hardsetting soil (Harrison et al. 1992)
- GPS-guided systems for controlling traffic to minimise the spread of compaction under vehicles (McKenzie 1998)

- crop rotation and tillage strategies that maximise the accumulation of organic matter and protect the soil surface (Fukuoka 1978; Lamarca 1996)
- mineral (gypsum or lime or both), organic and polymer soil conditioners to overcome soil physical problems such as dispersion in sodic soil (Abbott and McKenzie 1996; Wallace and Terry 1998)
- lime or dolomite to correct acidity (Rengel 2003; Upjohn et al. 2005)
- reduction of alkalinity through the application of acidifying nitrogen or sulfur fertiliser (Cornforth 1998)
- raised beds or land-forming to overcome problems on flat land (McKenzie 1998; Cass et al. 2004)
- drainage pipes to intercept spring-water from upslope (Skaggs and van Schilfgaarde 1999)
- structures for controlling erosion (Crouch et al. 2000)
- nutrient applications (either organic or synthetic, depending upon the preferences of the landholder) including the options described by Kinsey and Walters (1993), Peverill et al. (1999) and Johnston and Hollies (2003)
- procedures to prevent pesticide toxicities (Jackson 1983; Moore 1998)
- salinity – see *Salinity management*.

Soil amelioration for a particular site usually requires a unique combination of these methods.

Many farmers now understand the need to apply soil conditioners only where they are needed and at an appropriate rate. The traditional ‘blanket application’ of ameliorants such as lime, gypsum and nutrients – based on the analysis of bulked soil specimens – usually leads to deficiencies in some parts of a management unit and excessive amounts in others. Overdoses, apart from being expensive, can lead to excessive leakage of water and nutrients, and in some cases induce nutrient deficiencies.

For the agricultural zones of a catchment, the aim of soil management in most cases is to remove constraints and ensure production is near to the biological potential for the location. Farm produce, such as grapes, grown on spatially uniform soil is more likely to attract a premium because of the ability to achieve quality control. Soil specifications for wine grapes are discussed by White (2003).

Nevertheless, in some situations it is not economically feasible to overcome the soil limitations that have been identified (e.g. severe subsoil acidity, thin soil). In these situations, conversion of the land to perennial vegetation such as native trees and shrubs is likely to be the best option, both for the minimisation of off-site environmental impacts and maximisation of farm profitability.

Salinity management

Salinity is a widespread and serious problem in Australia. Management of soil, vegetation and irrigation are essential to prevent matters getting worse. When water drains beyond the root zone it can raise the watertable, and if the groundwater is saline, capillary rise can result in salinisation of the root zone. Soil surveys can be used to assess salt stores in the landscape, and the likely impacts of varying management practices on salt concentrations within the system.

Assessing the likelihood or risk of salinity in the root zone is difficult because salinity in the root zone is a result of the interactions between soil, the rate and direction of groundwater movement and groundwater quality and not soil properties in the root zone alone. A site’s position in the landscape, the permeability of layers beneath the root zone, and the presence or absence of continuous, shallow sand seams (aquifers) can have a larger influence on root zone salinity than the soil’s properties.

Assessment of salinity should not rely solely on point measurements (pits or cores) because:

- direct measurements of deep drainage are usually too costly at the intensity required
- soil texture, structure and pH on their own are not reliable indicators of likely deep drainage – soil that appears uniform can have variations in chemistry and physical properties that result in large differences in deep drainage
- small areas of permeable soil can leak large volumes of water – leaky areas tend to have small salt concentrations and they can be easily missed by grid surveys.

For these reasons, try to understand the distribution of soil in the landscape (see *Chapters 4* and *5*). Good examples relevant to salinity assessment are provided by English et al. (2002), Pain (2004) and Hulme (2003).

To guide assessment of deep drainage in land use for irrigation storages, Hulme (2001) combined information about geomorphology, colour aerial photographs and EM surveys to provide an initial stratification (including anomalies). EM-31 was used rather than EM-38 because signals from the latter are strongly influenced by the water content of the root zone that is affected by management. The larger the EC_a values the less leaky is the soil. It is still important to examine the soil because the signal is affected by several variables (see *Chapter 17*).

It is best to combine information from the soil pits and the EM survey. Use your understanding of geomorphology and colour aerial photographs to prepare an initial stratification – highlight any anomalies. Surveys with EM-31 and EM-38, ideally on soil that holds more than 50% of available water (Rhoades et al. 1999), are used to map patterns of variation in EC_a . Sample sites are selected by a Response Surface Sampling Design in the ESAP software (Lesch and Rhoades 2000). Soil chemical and physical properties of $EC_{1.5}$, chloride, cation ratios and soil texture are measured for a series of depths at each sample site. The $EC_{1.5}$ is converted to EC_e from measured $EC_{1.5}$, soil chloride and clay content by a relationship of Shaw (1999). A calibration between measured soil salinity (and other soil properties) is developed by ESAP, and calculated for each EM measurement location. The same measured soil properties can then be used to estimate potential deep drainage with the SALF software (Carlin et al. 1997), and ESAP is used to map variation in potential deep drainage rate.

Maps of salinity and potential deep drainage produced in this way have been used to select sites for production of salt-sensitive crops, and to pin-point small areas of excessive potential deep drainage in an otherwise clay-rich landscape.

Useful sources for information on reclamation of salt affected soil under irrigation include Salinity and Contaminant Hydrology Group (1997) and Skaggs and van Schilfgaarde (1999).

Monitoring and adaptive management

A soil should be monitored so that the soil management plans for a farm can be modified in the light of changes. Poor management often degrades soils. Establish a monitoring program for soil fertility, water use and water quality to optimise management. Closely link monitoring of soil with related programs for crop yield.

Data from devices for monitoring soil water (Charlesworth 2005) can be reviewed soon after harvest to assess root distributions and the effectiveness of water entry over the previous season. This information often is valuable for highlighting soil limitations such as compaction, subsoil acidity, hard-setting and salinity. The accuracy of RAW estimates from the initial soil survey can be checked against data on water extraction from professionally calibrated soil moisture probes.

Where poor quality irrigation water has been applied for several years through a drip irrigation system, soil properties (e.g. pH, salinity, concentrations of exchangeable sodium and magnesium) tend to become much more heterogeneous. Soil from mini-pits can be used to monitor soil quality under the drippers, between the drippers along the plant lines, under wheel tracks, and in the middle of the inter-row cover-crop zone in existing viticultural and horticultural developments. The impact of measures to counteract the adverse effects of poor quality water can also be assessed using this approach.

Where yield variation depends on crop nutrition, tissue testing (Reuter and Robinson 1997) is often preferable to soil testing, particularly for micronutrient assessment. Other potentially limiting factors such as diseases, pests and weather should also be monitored.

Interpreting yield maps and managing zones

Leading farmers have quickly recognised the benefits of modern precision agriculture techniques.

An example from the wheatbelt of Western Australia shows how yield maps and zone management can lead to more profitable agriculture with a reduced environmental impact. It comes from a dryland grain property of 5300 ha in the Great Southern region (350 mm annual rainfall). Precision agriculture improved profitability through better soil management (Alcorn 2003; G Fretwell and P Blackwell, pers. comm.). All field machines have consistent spacings for wheels and are steered via satellite guidance – this minimises the damage that results from compaction. The farm does not carry livestock, so all internal fences were removed to allow the boundaries of crop management units to be optimised.

The farmer had the following information to guide decisions on management.

- Three seasons of yield map data, and eight years of satellite imagery showing crop biomass.
- Maps of crop profitability, which allow productivity zones to be defined. The worst-yielding 7% of the farm (mostly zones with hard rock near the surface) was shown to be unprofitable even in years with excellent rainfall, so it is no longer cropped.
- Elevation data – supplied via the equipment for satellite guidance – on a 9-m grid with an accuracy of ± 0.1 m.

The farmer sampled soil for chemical analysis according to the productivity zones. This showed that more productive zones had a poor nutritional status (because of nutrient export via grain), whereas the zones producing less crop had an accumulation of nutrients from many years of blanket fertiliser application. The two zones will require contrasting fertiliser treatments in future.

The farmer's next task is to create maps of key soil factors in each of the cropping zones. Subsoil sodicity appears to be a major limitation on crop growth, so maps of soil dispersibility at key points within the root zone will need to be produced. Remote sensing, such as EM survey, and the digital elevation model are likely to be useful for the definition of soil factors between the soil sampling sites. Maps of soil dispersibility can then be used to prepare maps of application rates for gypsum and lime.

Soil pit inspections between the GPS-defined wheel tracks were recommended to assess the need for one-off deep tillage to relieve soil compaction caused by farm machinery and livestock prior to the introduction of the new farming system.

Improved techniques for soil management are likely to lead to crops with greater vigour and allow more efficient use of rainfall, which previously drained deeply. This improvement should help to alleviate the severe secondary salinisation that exists over much of this part of Western Australia.

Investing in soil evaluation

Wide-ranging economic analyses are needed to identify the optimal effort that should be devoted to soil assessment and management for various agricultural enterprises. Until this information is available, the authors recommend the following rate of investment in soil assessment for irrigated crops in Australia:

- initial assessments for new irrigation developments – about 3% to 5% of the establishment costs, which for wine grape production can be as large as A\$30 000 per hectare
- monitoring of existing irrigation and dryland developments – each year, about 0.5% to 1.0% of the estimated gross value of the crop being grown.

Such expenditure will pay for professionals to produce effective plans for survey and management. A team approach is usually needed, with inputs from irrigation engineering, drainage engineering, geomorphology, hydrogeology, geophysics, pedology, soil amelioration, viticulture, horticulture, agronomy, ecology and economics.

Summary

The commercial effort devoted to land evaluation in 2007 is small, but this is changing. Both land users and the Australian public recognise the impact of land degradation. The financial and environmental benefits of intensive evaluations of the soil are starting to be appreciated more widely by leading farmers and catchment managers.

To be effective, professionals engaged in intensive survey for agriculture must understand how to manage agricultural land in a way that maximises profitability with minimal environmental impact. They have to combine their expertise with that of professionals to advise managers on what are often complex problems.

A key task for the commercial land evaluator is recognising which characteristics are likely to be the most important at a specific site for a particular outcome. The practitioner must plan surveys accordingly. Comprehensive – but relevant – information from freshly dug pits forms the foundation of each new soil assessment. Sometimes remote sensing data can be used to improve the accuracy of a subset of the soil quality maps.

Having assessed and mapped soil condition at a new site, the land evaluator then has to inform the client what to do to remove as many as possible of the soil limitations that affect the performance of nominated crop or crops. Potential of the land following corrective measures needs to be discussed. Programs to prevent damage and to monitor changes in soil condition should also be devised for clients.

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Monitoring soil and land condition

NJ McKenzie

Introduction

The general proposition that our natural environment should be monitored is widely supported by natural resource management agencies, industry groups and community organisations. Monitoring data can provide feedback to assess the effectiveness of natural resource policies, determine the success of land management systems, and diagnose the general condition of landscapes. Furthermore, a set of environmental statistics is needed to match well-established economic and social indicators. The emergence of a range of large-scale environmental problems in Australia has added to the general demand for better information on trends in natural resource condition.

At the practical level, monitoring programs for various components of natural systems have been established in Australia. Well-established networks and procedures exist for weather, air quality, water quantity, water quality, particular aspects of land use (e.g. commodity production) and some biota (e.g. birds). Large archives of remotely sensed data from airborne and space-based platforms are also providing new ways of detecting change (e.g. Graetz et al. 1998; McVicar and Jupp 2001; see *Chapter 12*). Soil monitoring has been a more difficult task and this is consistent with experience in other countries (Schulin et al. 1993; Bullock et al. 1999; Mol et al. 2001). Indeed, in some countries with much better soil maps and databases than Australia, it has been debated even whether soil monitoring is feasible (Mol et al. 2001). However, there are now good examples of monitoring schemes and general agreement on strategies for determining changes in soil and land condition (e.g. Skinner and Todd 1998; Huber et al. 2001; Mol et al. 2001; Richter and Markewitz 2001; Bellamy et al. 2005).

No single approach can hope to satisfy all purposes. Information is required at various levels of sophistication, for many land uses, and across landscapes that are vast and diverse. Effective programs of monitoring have to be closely integrated with other activities that generate knowledge for managing natural resources – these include surveys of land resources, simulation modelling, field experimentation, and studies of environmental change (see *Chapter 1*).

This chapter centres on soil monitoring but it is set within the broader context of an integrated landscape approach. Most aspects of soil condition are closely related to vegetation, and land management more generally. For the sake of brevity, the term *land condition* will often be used, but the focus will remain on the interaction between soil, other relevant ecosystem components and land use. The emphasis is on monitoring that involves repeated measurements at a set of well-selected sites. Monitoring using remote sensing is considered elsewhere (see *Chapter 12*).

Rationale

The two main reasons for monitoring are the same as for land resource survey (see *Chapter 1*):

1. reduce risk in decision-making (Pannell and Glenn 2000)
2. improve our understanding of biophysical processes.

Monitoring programs need to be considered together with the mutually beneficial activities of mapping and modelling, and all three should then be set within the context of environmental change (Figure 1.1). Monitoring usually involves:

- establishing baselines for various ecosystem components
- detecting change over time, particularly deviations from natural variation.

Monitoring should be designed to test clearly defined ideas. However, reliable translation of monitoring results into management actions nearly always requires an understanding of *why* change is occurring. This translation usually requires more than monitoring data alone – an understanding of landscape processes is essential.

Approach and purpose

Four general approaches to soil and land condition monitoring can be recognised (Vaughan et al. 2001).

Simple monitoring

This involves the recording of a single variable at one or more locations over time. An example is trends in soil pH from the Representative Soil Sampling Scheme of England and Wales (Church and Skinner 1986; Skinner and Todd 1998) – one of the few long-term regional networks for monitoring soil change (see Figure 30.1). A statistically significant change is only evident with pH under permanent grasslands. Even though this is an example of simple monitoring (i.e. one variable), for reliable interpretation keeping track of land management is vital. Simple monitoring can be done across regions of varying extent – from the individual site, to the paddock, region or continent.

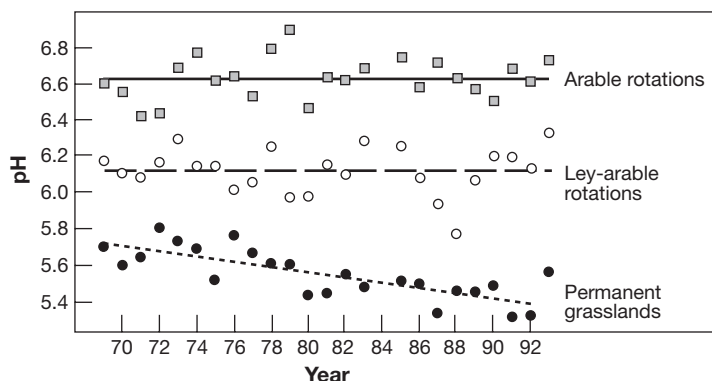


Figure 30.1 Trends in mean pH (CaCl_2) from the Representative Soil Sampling Scheme of England and Wales. The only statistically significant trend occurs in permanent pasture (Skinner and Todd 1998).

Survey monitoring

Certain environmental problems appear at discrete locations (e.g. surface outbreaks of salinity), but almost invariably no monitoring record exists at these sites or at other nearby locations where the problem manifests. Monitoring surveys aim to provide a substitute for the historic records by undertaking a survey of current conditions across a given region. Survey monitoring assumes:

- soils at different locations were once the same in every respect
- some form of land use history is available for each location
- sampling of sites with different management histories allows inferences to be made about the impact of land management over time – *space is substituted for time*.

The series of studies on the effects of agricultural management in northern Tasmania exemplify the approach (Sparrow et al. 1999; Cotching et al. 2001, 2002a, 2002b).

Paired-site studies are another example of survey monitoring. In most cases, sampling is undertaken at the same time from a relatively natural site (typically forest or woodland) and adjacent disturbed site (typically under some form of agricultural use). While sampling within each site may be statistically based, the paired site is usually selected without any form of randomisation. See Bridge and Bell (1994) and Conteh (1999) for a review and example of the approach.

The main limitation of survey monitoring is the assumption that space can be substituted for time. It is usually difficult to confirm that sites with different management histories were once the same, and that the assumed starting point provides an appropriate baseline. Interpretation of results is also hindered by the frequent lack of information on management history.

Proxy monitoring

Another way of overcoming the lack of long-term monitoring records involves the use of proxy or surrogate measures to infer historical conditions.

The results of proxy monitoring of soil are equivocal. Many schemes for inferring soil condition using surrogates have been proposed (e.g. Hamblin 1998) but few have been rigorously tested. Increasingly, existing land resource data, commodity statistics, and remotely sensed data are being used to compute balances of nutrients or parameterise simulation models (SCARM 1998; NLWRA 2001). These approaches require careful testing. For example, sequences of remotely sensed images can be used to measure land cover. With appropriate field observation, correlations can be developed between the land cover classes and soil attributes (e.g. soil carbon) – if reliable, these relationships can be used in conjunction with the remote sensing to monitor the attribute. In most cases, such proxy monitoring will be less sensitive for monitoring than direct measurement, but it may provide other advantages such as information on spatial patterns. Surrogate measures will often be needed as an interim measure until the results from more direct monitoring methods become available.

Integrated monitoring

Simple, survey or proxy approaches are useful but they are generally unable, by themselves, to reveal why changes are occurring. This requires a different strategy for gathering information. Integrated monitoring (Munn 1988; Vaughan et al. 2001) has the overall objective of recording and understanding changes in the total landscape. It aims to:

- establish cause and effect
- derive scientifically based programs for managing natural resources

- measure the response to land management
- provide early warning of emerging resource issues.

Integrated monitoring involves studies that are long-term and interdisciplinary. It is often centred on a calibrated catchment where measurements aim to develop a detailed balance of the inputs and outputs (water, nutrients, solutes, sediment, contaminants) along with intensive biological monitoring of the terrestrial and aquatic components of the landscape. Monitoring is usually carried out in conjunction with research projects and some form of manipulation of subcatchments is involved (e.g. clearing, burning, different grazing regimes). The success of various long-term integrated monitoring studies (e.g. Hubbard Brook, New Hampshire, United States (Bormann and Likens 1967; Likens and Bormann 1995)) has led to the establishment of several networks of long-term ecological research sites in several countries (e.g. Sykes and Lane 1996; Robertson et al. 1999; Vaughan et al. 2001; LTER Network 2006).

Defining the purpose of monitoring

Virtually every text on monitoring emphasises the need for developing clear objectives to guide measurement and data analysis. Contrarily, however, most evaluations of long-term monitoring programs and field experiments reveal that most benefits were unforeseen at the outset (e.g. Leigh and Johnston 1994). Although critical, defining the purpose of monitoring can be difficult because of the inescapable need to incorporate flexibility – how else can the unexpected be detected?

The need for a whole-system view

Whatever its purpose and design, a conceptual model of how landscapes operate is an essential first step in devising a monitoring system. Landscapes have a range of intrinsic properties that need to be considered in relation to monitoring (Boyle et al. 2002).

- ▶ The behaviour of many landscapes reflects the action of positive and negative feedback loops. Monitoring individual components separately (e.g. only soil but not vegetation and hydrology) will fall short in understanding whole-system behaviour.
- ▶ Landscapes are comprised of hierarchies of processes. Some scales of observation are more effective than others for monitoring change. While supporting information collected at a broader scale is needed for context, information collected at a more detailed level is needed for a clear understanding of mechanisms of change (Allen and Hoekstra 1992, see *Chapter 3*).
- ▶ Some landscapes may have multiple steady states and exhibit sudden and unpredictable behaviours – simple, survey or proxy monitoring will often be of limited value in these circumstances because they do not yield information on the underlying causes of change.
- ▶ Some processes within landscapes may also exhibit chaotic behaviour and have limited predictability, regardless of the level of information and modelling capability.
- ▶ Landscapes and soil properties naturally change with time. Different patterns and rates of change will affect how one designs a suitable monitoring scheme. Some change is slow and gradual (e.g. acidification) while in other cases it is episodic, rare and not easily reversed (e.g. erosion). In some cases, monitoring will just not be feasible.

These different forms of system behaviour present many challenges to a scientist seeking to provide useful information to a decision-maker. In some cases, cause and effect are straightforward, and the variables to monitor are self-evident (e.g. soil acidification of individual paddocks). In other instances, a much broader ecosystem view may be required (e.g. to assess the potential cascade of effects of landscape-scale acidification on ecosystem structure and function in waterways).

Traditionally, scientists trained in the reductionist mode tend to restrict their work to investigations of relatively simple systems where cause and effect can be isolated and understood (e.g. conventional agronomic experimentation). How then to design a monitoring scheme framed around an understanding of a multifactorial system? Understanding a system's behaviour is not of purely theoretical interest because problems in managing natural resources across Australia relate to landscapes that exhibit behavioural traits typical of complex systems: system flips, bifurcations, hysteresis, episodic perturbation, unpredictability. McKenzie et al. (2002a) provide examples, but clear prescriptions are lacking at present.

Sampling

Scales of variation

Soils vary vertically, horizontally and through time. Yet land resource survey has focused almost exclusively on characterising variation in the vertical (e.g. soil profiles) and horizontal (e.g. map units) dimensions. Most characterisation has been qualitative with a strong focus on morphological properties; less attention has been given to chemical and physical properties, and virtually no consideration of soil biology has appeared.

Although there is a degree of correlation between soil properties, the substantial literature on spatial variation (e.g. Beckett and Webster 1971; Wilding and Drees 1983; Burrough 1993) demonstrates that soil properties have varying levels of covariance. Furthermore, the proportion of variation in a particular attribute accounted for by a land resource map can be very low (e.g. <50% and often <30%).

Of great importance to monitoring is variation over short distances. Beckett and Webster (1971) concluded: 'up to half the variance within a field may already be present within any m² in it'. This large short-range spatial variation of most soil properties has two major implications for monitoring.

1. Most measurements of soil properties involve the collection of a specimen – sampling is destructive and subsequent measurements are done on separate specimens. Short-range spatial variation is problematic because spatial and temporal patterns can be easily confounded unless there is sound sampling and sufficient replication.
2. The large variation in most soil properties implies that a proportionally large effort in replication is necessary to detect trends – the signal to noise ratio is typically low.

Statistical issues

Devising a statistical framework for monitoring involves many considerations and statisticians should be involved in studies from the outset (see *Chapter 20* and de Gruijter et al. 2006). Programs of monitoring that do not have a solid statistical foundation will be at best flawed, and, at worst, erroneous and a complete waste of resources.

Sampling

The principles of sampling described in *Chapter 20* are applicable and the following discussion is restricted to general issues of statistical design relevant to soil monitoring regardless of the geographical extent (e.g. paddock, experimental catchment, regional network of sites, continent).

Clearly define the *scope of inference* of a monitoring program. This specifies the domain over which the results are to apply. It may be defined in purely geographical terms (e.g. local region, state, continent) or use other criteria (e.g. rainforest, cropping lands, public lands).

From this, define the *target population*. This refers to the aggregate of units that make up the scope of inference. For example, if the scope of inference is Australia's cropping land then the target population may be defined as all fields used for cropping in a specified year. In contrast, the *sampled population* is the aggregate of units from which a *sample* or subset of units is selected for inclusion in the study (Cochran 1977; Olsen et al. 1999).

Make sure the target and sampled populations coincide so that statistical methods can be used to make inferences about the target population on the basis of the sample. This is not as simple as it seems (see *Chapter 20*).

Location and site layout

To begin, clearly define the dimensions of the soil individual (see *Chapter 20*) and prepare a plan for repeated sampling over the required period). Locate sample points and any relevant site boundaries to within 0.1 m of their true position. This can be achieved using a Differential Global Positioning System (DGPS). In some circumstances (e.g. remote areas), a local benchmark may have to be used for the DGPS base station and locations will only have the required relative accuracy. Absolute accuracy will be achieved only when the local benchmark is tied to the standard geodetic framework for topographic survey. Clearly identify the local benchmark so it can be located at a later date. If DGPS is not an option, mark the site permanently. The procedures used to mark and locate the Rothamsted long-term experiments are worth emulating (see Leigh et al. 1994); they involve a system of posts along fences (used for triangulation) and sunken pegs (below the plough layer) at accurately determined distances from the fences. Store the records relating to the site layout in at least two locations (Likens 2001).

Prepare and enforce clear protocols and controls for machinery operating on or near monitoring sites. Clearly mark access tracks and prevent traffic on the monitoring plot unless it is part of the system of land management being studied.

Lateral processes

Many processes controlling soil formation and landscape function involve lateral fluxes of sediment, solutes and water. The risk is that monitoring sites comprised of soil *individuals* (even a well-organised set along a toposequence) will fail to appropriately capture changes in soil condition. In cases like this, monitoring will require instrumentation and measurement of larger scale entities (e.g. hillslopes), possibly with nested sets of soil individuals. The appropriate design will depend on the study objectives, understanding of landscape processes and resources available.

Purposive sampling

Most soil monitoring data in Australia have been derived from purposive sampling and this constrains their general use. In most districts, the selection of monitoring and experimental sites for assessing the impact of land use is also highly constrained by the availability of areas with minimal disturbance or appropriate land management. Areas with limited disturbance (notional baselines) are often in such a near pristine condition because they started out different to the surrounding landscape (e.g. they had lower fertility).

Nutrient testing is undertaken at the level of the paddock, and protocols for sampling paddocks are well established. The problem is, however, that interpreting regional trends in nutrient status on the basis of these data requires knowledge of the reasons why the paddocks were selected in the first place. For example, were they areas with nutrient deficiencies or perhaps better-class lands subject to more intensive management? Either way, bias might be substantial.

If purposive sampling is unavoidable, develop a set of explicit criteria tailored to the particular study. They need to state:

- the resources available for sampling
- criteria used for stratification of the study region (whether it be an experimental plot, catchment or region)
- criteria for allocating samples to strata
- rules used for locating observations in the field (e.g. Petersen and Calvin 1986)
- regions excluded from sampling.

With this agreed procedure, the field operators can then:

- select several replicate sites in a specific region
- use different field operators to select sites in a region
- classify each site according to the criteria
- select the best sites based on these criteria.

Statistical sampling

Unpalatable though it may sometimes be, the only sure way of avoiding bias inherent in purposive sampling is by *statistical sampling* (see *Chapter 20*). There are many options for designing an appropriate statistical sampling scheme: de Gruijter et al. (2006) provide the definitive account. Olsen et al. (1999) provide a general review of statistical issues relating to major monitoring programs in the United States, including the Natural Resources Inventory (NRI) (Nusser and Goebel 1997; NRI 2000).

Inevitably, objectives and questions will change during a long-term monitoring program so, as foreshadowed earlier, flexibility should be built in. Aim for simplicity in the initial design and allocate limited stratification and equal inclusion probabilities (Overton and Stehman 1996). Minimising sample structure actually maximises flexibility for later measurement programs that might involve new variables.

Although statistical sampling avoids bias, it is not a panacea: sometimes it may be impossible to apply when monitoring is expensive and funds permit only limited replication. For example, very few agencies have been able to replicate paired catchment studies across regions (although most such studies have replication within the experimental area). Similarly, large long-term ecological research sites are rarely replicated although efforts to develop coordinated networks are an attempt to overcome the problem (e.g. Sykes and Lane 1996; Vaughan et al. 2001; LTER Network 2006).

Fixed location versus flexible network

Most monitoring networks operate with fixed sampling locations. However, land management may change inadvertently (or deliberately) once the location of a site has been set. Fixed locations may also lead to a gradual attrition in site numbers as a result of unexpected land use changes (i.e. sites may no longer conform to the *a priori* classification used during the network design) (Mol et al. 1998).

These problems can be overcome with a network of shifting locations. For example, the Representative Soil Sampling Scheme for England and Wales involves resampling of farms surveyed both 10 years and 5 years earlier (on each farm four fields are initially selected at random for sampling). In addition, 60 farms are resurveyed that were first sampled 5 years earlier and 60 new farms are selected each year. Once farms have been surveyed on three occasions, they are discarded from the study. This reduces the risk of feedback to farms that remain in the survey for long periods; it also introduces new farms to make up for those lost as a result of urbanisation and road development (Skinner and Todd 1998). The major drawback with a flexible network is that trends are more difficult to detect.

Frequency

Some soil properties exhibit natural cycles on a daily and seasonal basis. Failure to account for these makes the early detection of trends more difficult. For example, solute concentrations, pH and the availability of various nutrients vary seasonally. Consistency in the timing of measurement is, therefore, necessary.

Replication and bulking within the soil individual

Estimating the mean value for a soil individual is often complicated by logistical factors. Obtaining random replicates from the surface and near-surface layers is straightforward when a 25 m × 25 m area is used to define the soil individual (with the lower boundary coinciding with the weathering front). But collecting a random sample of undisturbed soil cores from deeper layers is more expensive. Every effort should be made to enforce statistical control and achieve efficiency through stratification and bulking. Bulking involves the physical aggregation and mixing of soil specimens to create a less variable specimen (see *Chapter 16*).

Stratification within the soil individual

Although simple random sampling within a soil individual is feasible, efficiency is nearly always improved by using stratified random sampling and this approach is recommended here (Papritz and Webster 1995a, b). The simplest form of stratification is with a simple grid. Soil observations are randomly allocated within strata. Stratification using other variables is also possible; for example, microtopography (e.g. gilgai shelves, depressions), perennial vegetation (e.g. tussock grasses, bare ground) or rock outcrop. Avoid stratifying with variables that are prone to operator bias or are of an ephemeral nature (e.g. annual vegetation) because they might create confusion during later phases of sampling.

Many layouts can be used for soil monitoring sites and some options are found in Papritz and Webster (1995b), Hornung et al. (1996) and de Gruijter et al. (2006). The layout in Figure 30.2 is intended as a starting point for designing a site for monitoring soil. There has been no allowance for the installation of *in situ* measurement or collection systems (e.g. access tubes for neutron moisture meters or soil solution samplers). Figure 30.2 represents a 25 m × 25 m soil individual subdivided into 25 cells. The design allows for five periods of sampling. For each period, five cells are selected randomly, one from each of the five blocks (i.e. columns A–E). In Figure 30.2, each cell is divided into four strata and a sample is randomly located in each. Bulking of soil specimens

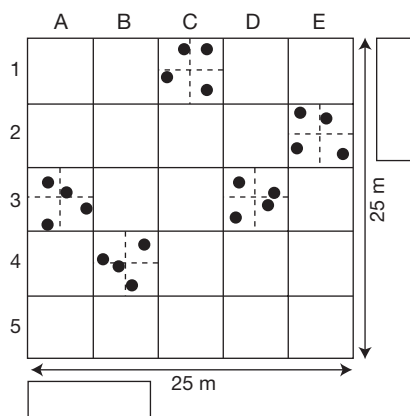


Figure 30.2 A possible layout for a soil-monitoring site. The rectangular areas outside the site enable profile characterisation.

is possible at the level of the cell, block or site depending on the overall design. The rectangular areas outside the site are used for soil pits to enable profile characterisation.

Measurement

Accurate and precise measurement is essential in monitoring and achieving it requires clear protocols for all activities. Use standard methods for laboratory measurement wherever possible (e.g. Klute 1986; Rayment and Higginson 1992; McKenzie et al. 2002b). Some aspects of monitoring require extra specification and McKenzie et al. (2000) provide an example of rules and guidelines for monitoring soil carbon beyond those found in Rayment and Higginson (1992).

Match measurement methods with those used by other investigators doing similar studies (see below) and calibrate against standard specimens. Do not change analytical methods (or sampling procedures) without thoroughly testing the effect of the new procedure against the long-term record. However, do not casually adopt methods or procedures developed for one particular location or study without careful testing and justification (Likens 2001). Pilot studies are essential for testing measurement methods.

Site and soil characterisation

Site and soil characterisation provides:

- a basis for extrapolating results to other similar sites and soils
- a means for grouping or stratifying sites to aid measurement and analysis
- insights into anomalous or unusual results.

Characterise the site and profile when the monitoring site is established. In Table 17.9 the minimum data set is specified, but this should not restrict more detailed characterisation if resources permit (e.g. Table 17.10). Soil pits for this purpose are located beside the main plot (Figure 30.2). The soil properties to be monitored on a regular basis will be restricted to a much smaller set.

Monitored soil properties

Most of the recommendations on sampling and measurement that apply to site and profile characterisation (see *Chapters 16 and 17*) also apply to soil properties monitored on a regular basis. The selection of soil properties for monitoring will be dictated by study purpose, accuracy and precision of the measurement method, and cost. Soil properties with large short-range variation are difficult to monitor.

Sparling et al. (2002) have evaluated a wide range of soil variables for monitoring under New Zealand conditions. They identified seven essential soil properties (Table 30.1). These are relevant to Australian conditions, particularly the temperate south. However, the proposed set needs to be evaluated for land uses and soils that are widespread in Australia. For example, it would be logical to add soil properties sensitive to changes in sodicity and electrolyte concentration (e.g. dispersive potential of clay, Rengasamy 2002), while more appropriate measures of nutrient availability may be needed for the strongly weathered soils that cover large parts of the continent.

Measurement *in situ*

Most measurements of soil properties involve the collection of a specimen – sampling is destructive and subsequent measurements are undertaken on separate specimens. Monitoring would be greatly simplified if reliable measurements could be undertaken *in situ*.

In situ measurement is routine in field experiments. Established techniques include measurement of soil water content using neutron moisture meters, capacitance probes and time

Table 30.1 Soil properties recommended for monitoring in New Zealand (Sparling et al. 2002)

C, carbon, N, nitrogen, P, phosphorus.		
Soil property	Soil quality information	Applicable to
Total C	Organic carbon content	All soils
Total N	Organic matter nitrogen status	All soils
Mineralisable N	Readily decomposable organic nitrogen	All soils
Soil pH	Soil acidity	All soils
Olsen P	Phosphate available to plants	All soils
Bulk density	Soil compaction	All soils
Macroporosity	Soil aeration and compaction	All soils
QuickTest cations	Calcium, magnesium and potassium available to plants	Only necessary where the nutrient balance is important
Aggregate stability	Stability of peds	Soils used for cropping and horticulture

domain reflectometry. Various sensors and data loggers are used routinely for monitoring groundwater levels. Instruments for measuring chemistry of the soil solution (e.g. pH, redox potential, electrical conductivity, concentrations of individual cations and anions) are becoming more widely used (Birrell and Hummel 2001; Viscarra Rossel and McBratney 2003). Resin capsules provide an alternative means for characterising chemistry of the soil solution (Skogley and Dobermann 1996; Skogley et al. 1996; Qian and Schoenau 2002). The advantages of *in situ* measurement include:

- avoidance of artefacts and variation associated with specimen extraction and preparation
- non-destructive sampling and limited disturbance of the monitoring site
- capacity to generate high-frequency measurements
- compatibility with digital technologies and automatic downloading of data via mobile phone networks.

The main disadvantages of *in situ* measurement are:

- most technologies require regular maintenance and field inspection
- costs can be significant
- disturbance associated with either the process of installation, or the actual sensor (e.g. impedance of drainage), can cause artefacts
- measurement may be restricted to a relatively small soil volume
- environmental conditions within the soil are not controlled in the same way as for laboratory measurement (e.g. seasonal variations in temperature and electrolyte concentration)
- reliable technologies exist only for a limited range of soil properties.

Monitoring soil condition with limited field measurement

The discussion so far has assumed some form of direct measurement in the field. Many proposed (and some existing) schemes for the proxy monitoring of soil have limited or no field measurement (e.g. Hamblin 1998; NRI 2000). Methods that involve direct measurement of soil properties are preferred for the following reasons:

- variables can be selected that relate closely to the biophysical processes of interest
- sampling and measurement errors are minimised and, as a result, change over time can be detected more readily.

Unfortunately, direct measurement is relatively slow and the generalisation of results from a site to large regions can be problematic. Remote sensing generates data with a complementary set of advantages and disadvantages to direct measurement. The disadvantages include the following:

- it can be difficult relating remotely sensed variables (e.g. spectral reflectance) to soil variables controlling biophysical processes, although this is changing through the use of hyperspectral methods and temporal analysis (e.g. McVicar and Jupp 2002, see *Chapter 12*)
- most measurements relate to the land surface or near-surface layers.

Notwithstanding, remote sensing has some distinct advantages for monitoring:

- measurements are made across complete regions, often at fine resolution
- the frequency of measurement is high compared to direct field measurement
- changes in spatial pattern can be readily detected.

To enable reliable interpretation, monitoring via remote sensing requires a careful process of calibration with field measurements (see *Chapter 12*). Remote sensing is central to the integration of mapping, modelling and monitoring.

Data management

Long-term monitoring may proceed for decades and involve the collection of large quantities of data. Apart from the Bureau of Meteorology, most Australian agencies involved in managing natural resources have a poor record of data management and this problem has been made worse by substantial institutional changes in recent years. Data from many long-term (> 25 years) field experiments are not readily accessible and there has been a lack of adequate reporting of even basic research findings (Grace and Oades 1994).

Nevertheless, there have been some positive gains in the management of soil data from surveys resulting from the establishment of data exchange standards and the wide acceptance of standard procedures for soil description and measurement (McDonald et al. 1990; Rayment and Higginson 1992; McKenzie et al. 2002b). Creating systems for the long-term management of data is a challenge and one that should not be underestimated. From long experience of many long-term agricultural experiments and ecological monitoring studies, several clear lessons can be distilled.

- ▶ There will be many changes in managerial, scientific and technical staff over several decades. Therefore, record all aspects of the monitoring program (Jones et al. 1995).
- ▶ Maintaining records goes well beyond a database of soil properties, plant yields or other outputs, so include ancillary data that capture details of land management practices, anomalies of particular years, observations of pests and diseases, and any other factors considered relevant to future interpretation (Leigh et al. 1994).
- ▶ Ensure continuous data sets are constantly updated, scrutinised for errors, and rigorously reviewed. Assess and record data quality (Shampine 1992).
- ▶ Data type and quality (e.g. with respect to sampling procedures, measurement methods) must be consistent and comparable (Shampine 1992).
- ▶ Store copies of records in several locations (Likens 2001).
- ▶ Establish clear lines of management responsibility to ensure individuals with appropriate training undertake measurement and data management.

- ▶ Report results at regular intervals (preferably in a form available to the public).
- ▶ During the design phase, explicitly address procedures for data management and analysis.
- ▶ Always remember that stability, interest and dedication of responsible individuals, institutions or agencies are critical to the success of long-term monitoring (Likens 2001).

Archiving

It bears repeating that soil specimens collected during a monitoring program should be stored in secure archives. This can add immense value to a monitoring program as demonstrated by the experience at Rothamsted in England where the archive of crop and soil specimens is now as valuable as the experiments from which they are derived (Leigh et al. 1994). The Rothamsted archive has been used for many purposes including:

- retrospective studies of nutrient balances
- determining changes in soil organic matter
- tracking the accumulation of industrial inorganic and organic pollutants.

Soil archives in Australia have been associated with research organisations or agencies undertaking land resource assessment. For example, the CSIRO National Soil Archive has been used to:

- analyse specimens from across southern Australia to allow rapid assessment of the distribution of soil with toxic levels of boron (at a fraction of the cost necessary for new field work)
- analyse carbon profiles for a range of Australian soils
- calibrate new methods of analysis.

The archive also includes many specimens collected prior to agricultural development in areas that now sustain heavy application rates of pesticides and herbicides.

Management of soil archives in Australia has been less successful than data management. The following recommendations are based on experience with the CSIRO soil archive, the Rothamsted archive (Leigh et al. 1994), the Sample Archive Building at the Hubbard Brook Long-term Ecological Research Site (Boone et al. 1999) and guidelines for the UK Environmental Change Network (Hornung et al. 1996).

- ▶ Store specimens in long-lasting containers with permanent, unambiguous labels that record site number, location, depth, date of sampling, fineness of the specimen (e.g. < 2 mm) and other relevant identifiers. Fix labels on both the container and lid and place a copy of the label on plastic or similar material inside the container with the specimen.
- ▶ Integrate the soil archive inventory and database from the monitoring program. Specimens must be matched to database records (e.g. using bar coding). Individuals responsible for the archive should also be responsible for data management.
- ▶ Develop efficient methods for storage and retrieval.
- ▶ Ensure adequate space for long-term storage.
- ▶ Keep the archive air-dry at room temperature and in a secure location with a low probability of water damage (e.g. broken pipes, flooding), chemical contamination, fire or other problems. Minimise temperature fluctuations to prevent condensation inside containers.
- ▶ Long-term storage of field-moist specimens in refrigerators or freezers is generally not recommended because of inevitable power failures.

- ▶ Before any form of analysis or storage, homogenise the fine-earth fraction (<2 mm) so that the analysed and stored specimens are identical.
- ▶ Have a written policy on use and access to the archive along with a log of activities and users. Provide the original investigators with free and easy access to the specimens.
- ▶ Subsampling archived soil is wasteful because individuals often take more than they need. It is better for users to take the complete specimen, use the amount required, and then return it. To protect against loss of material, archivists can maintain a subsample for use only in the event that the working specimen is lost.
- ▶ Changes in soil properties will occur during storage and these should be monitored by periodic analysis of reference materials or in-house standards.

Consider lodging soil specimens and data collected from monitoring sites with the CSIRO National Soil Archive in Canberra.

Change over time

Choosing an appropriate frequency of measurement will depend on the objectives of the study, understanding of system behaviour, patterns of variation in the relevant soil properties across the landscape and through time, statistical design (e.g. sampling method, sample size, degree of replication, bulking strategies), measurement technology, and resources.

The best frequency for sampling can often only be determined after an analysis of preliminary results. Determining an appropriate frequency of measurement is as important as the length of measurement because short-term dynamics may be of over-riding importance. The duration of measurement needs to be at least as long as the phenomenon being evaluated, or scaled to the frequency of the event being studied (Likens 2001). Long-term measurements (i.e. spanning decades) are normally necessary to detect soil change (Richter and Markewitz 2001).

The separation of temporal and spatial variation has already been highlighted as a major methodological challenge for soil monitoring. The capacity to obtain an accurate and precise estimate at any point in time is a critical factor in determining whether soil change can be detected in a cost-effective manner – it will take far longer to detect a trend when measurements have low accuracy and precision.

McKenzie et al. (2002a) showed there is enormous variation in the sample size required to detect change in different soil properties and these sample sizes are markedly large if change is to be detected within 10 years. Their results suggested that some changes are easy to detect (e.g. in pH and organic carbon) while others require impossibly large numbers of samples (e.g. hydraulic conductivity).

The essential requirement for monitoring soil change is to analyse the differences between individual sites over time. The alternative – comparing the mean value of a soil property across all sites at time zero with the mean for all sites at a later time – is an inefficient and ineffective method for detecting change. This is depicted in Figure 30.3. The efficiency gained from examining differences between individual sites over time (Figure 30.3b) can be achieved only if measurements are repeated at the same site over time.

Separating soil change in space and time: the role of maps

There is a widespread and appealing misconception that qualitative maps of soil and land resources (i.e. based on purposive sampling) provide a practical baseline for monitoring (e.g. those presented in NLWRA 2001). A corollary is that maps can be generated at intervals by successive surveys to provide an indication of changes in soil condition. This view is misguided for the following reasons.

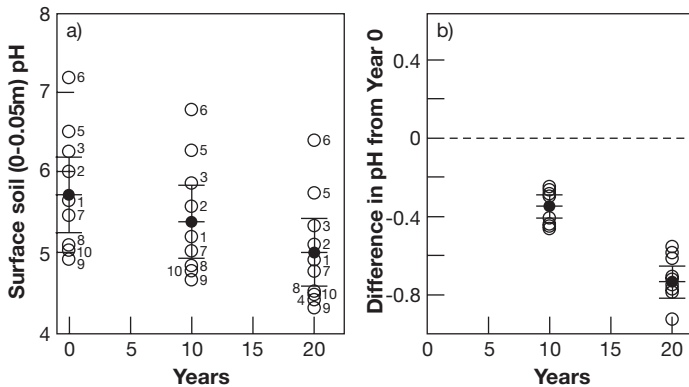


Figure 30.3 Hypothetical example of pH change over 20 years for 10 sites (site numbers shown in (a)). In (a) the average pH for each time interval is calculated and presented as a mean (•) with 95% confidence intervals – the intervals overlap for the three times, so no statistical significant change is detected. In (b) the information for each site is retained in the analysis and the difference in pH for each site from Year 0 is plotted. The resulting confidence intervals are much smaller and a strongly significant statistical difference is detected. The analysis in (b) is not possible if different sites are used in each period of sampling.

- ▶ The predictions derived from a soil map for a given soil property at a specified location will have wide confidence intervals. This is caused largely by the short-range variation exhibited by most soil properties. As a result, maps at best provide imprecise snapshots of soil properties at some point in time – more sensitive methods are necessary to detect soil change.
- ▶ Virtually all soil and land resource maps produced in Australia rely on purposive sampling so there is no way of estimating their accuracy and precision without supplementary sampling.
- ▶ The field measurement program for a survey focuses on sites that provide the maximum amount of information on factors controlling the *spatial* pattern of soil variation. As a consequence, some soil or landscape units that occupy large areas may not be sampled often because they are easy to map, while other less widespread units may receive a disproportionate sampling effort.
- ▶ The target population for monitoring rarely coincides with the sampled population for land resource survey. This is usually unavoidable given the resources available for surveys of soil and land resources. Furthermore, surveyors have to sample at many locations across the complete landscape whereas it is usual for only a portion of the landscape to be of interest for monitoring (e.g. intensively used or vulnerable zones).

Despite these issues, soil and land resource maps have a critical role in soil monitoring for the following reasons.

- ▶ Rates of soil change under different systems of land management are highly dependent on the soil type. Some processes (e.g. leaching, organic matter oxidation, acidification) occur at faster rates on given soil types. Soil maps provide a means for stratifying a region and for locating monitoring sites. They also provide essential information for interpreting the results from monitoring.
- ▶ Soil and land resource maps provide a basis for identifying priority regions for monitoring (e.g. those prone to degradation). Rather than forming a baseline for monitoring, they provide a means for focusing and ensuring the efficiency of soil-monitoring programs.

Modelling and monitoring as complementary activities

Insight can be gained into the optimal design of a monitoring program through some preliminary statistical analysis. This can be undertaken in a more sophisticated way through the use of simulation models. For example, farming systems models such as APSIM (Keating et al. 2003 or PERFECT (Littleboy et al. 1989) can be used in conjunction with long-term weather records to generate a range of scenarios. The trends in soil properties generated by these models can provide more realistic representations of the patterns of change (e.g. non-linear or episodic). Statistical analysis of the simulation outputs can then be used to design sampling schemes with appropriate replication and frequency of measurement.

Data analysis

The analysis of monitoring data is concerned with the detection of trends, cycles, outliers and noise. A summary of relevant data analysis methods (e.g. time series analysis) is beyond the scope of this chapter. Good treatment of statistical methods are provided by Manly (2000) and de Gruijter et al. (2006), whereas a summary of methods for water quality assessment (also relevant to soil monitoring) is provided by ARMCANZ/ANZECC (2000). As with most aspects of monitoring, advice should be sought from a qualified statistician. However, an overly rigid statistical approach (e.g. complete reliance on tests of statistical significance) has some limitations.

Statistical significance and lines of evidence

Soil monitoring in Australia is gaining support but it will be years before conclusive results will be generated by monitoring programs of the type recommended by McKenzie et al. (2002a). There will still be situations where soil change is suspected but conclusive data are lacking. Decision-makers require advice on likely changes in soil and land resource condition and they cannot wait until there is statistical certainty in trends from long-term monitoring sites. Interim procedures are required so that assessments of change can be based on risk, probability and expert opinion (Vaughan et al. 2001). There are several options:

- results from simulation modelling help assess whether suspected trends in soil condition are likely to become clear
- panels of experts can be assembled to undertake critical reviews and judge whether a perceived problem is significant – these panels draw on all lines of evidence (e.g. process understanding, published literature, anecdotal evidence, initial monitoring results, simulation modelling)
- panels of experts can also engage in creative scenario writing to thoroughly consider a range of future states. These scenarios can be used to devise programs of investigation that lead to early detection (Munn 1988).

Community, landholder and industry programs

A range of programs and guides to soil monitoring have been produced for landholder and community groups (e.g. Hunt and Gilkes 1992). Most have a strong focus on improving land literacy and they have been of great value in contributing to improved land management. Although there is potential for capturing the information gathered from such programs to construct district or regional overviews, the task of detecting soil change using this approach will be very difficult because of issues relating to accuracy and precision of measurement, quality control, and inevitable bias in the location of monitoring sites. Most community programs encourage a loose form of survey monitoring rather than activities with strict schedules for repeated observations at specified locations. A large investment would be necessary to upgrade community and landholder programs to ensure soil data of a sufficient standard.

Agricultural industries collect very large quantities of valuable analytic data each year, with most relating to plant nutrition. There is a need to create partnership schemes to encourage the sharing or pooling of such data. Pooled data would provide industry groups with information on trends in resource condition. For the same reason, they would be invaluable to public agencies responsible for managing natural resources. The full value of data sets generated by industry will be realised only when evaluations are undertaken of the validity of regional-scale conclusions. In particular, statistical assessments of bias, precision and accuracy are required. It may be difficult to ensure one key feature for efficient soil monitoring – repeated measurements at the same sites over time.

Conclusions

A much greater effort is now being devoted to monitoring soil and land condition (e.g. NLWRA 2005). There are many technical and institutional issues. The strategy outlined by McKenzie et al. (2002a) is starting to be implemented. Expert panels have been convened to advise on monitoring of soil acidification, soil organic carbon and soil erosion by wind and water.

How complementary sources of information on natural resources can be gathered over a range of scales is summarised in Figure 30.4. Table 30.2 provides a checklist of design considerations. Specific challenges for detecting soil change over time are as follows:

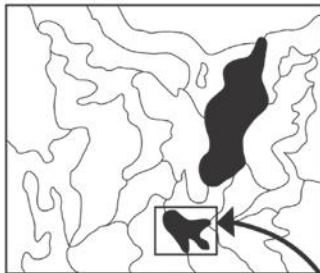
- ▶ A large sampling effort is often required to detect the relatively small changes over time against the often-large spatial fluctuations over a range of scales.
- ▶ Some soil properties can be readily monitored (i.e. those that are less spatially variable, responsive to management, and easy to measure) while others are impractical because of large spatial variation and cost of measurement.
- ▶ Monitoring soil change at local and regional scales can be done. However, it is essential to repeat measurements over time at the *same* site and to then analyse differences between individual sites over time. The alternative of comparing the mean value of a soil property across all sites at time zero with the mean for all sites at a later time is inefficient and ineffective (Figure 30.3).
- ▶ Monitoring soil change relies ultimately on good quality measurement at representative field sites, often over extended periods (i.e. decades).
- ▶ Information on land management is critical for interpreting the results of monitoring.
- ▶ Maps of soil properties, land types or so-called sustainability indicators are an inefficient means for detecting change because their predictive capability for a given location is low, meaning that comparisons of maps prepared for different times will have a very low accuracy and precision. That said, the maps are valuable because they show patterns of resource condition and provide an essential tool for designing and prioritising monitoring efforts. They are also necessary for analysing and generalising results from a monitoring program.

At a more general level, programs of monitoring should have the following features.

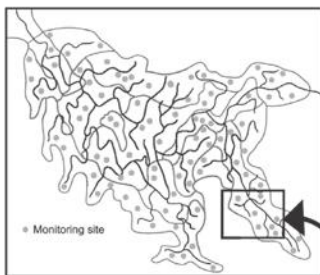
- ▶ A clear purpose closely linked to a decision-making process at the farm, catchment, region, state or national level, or a scientific focus.
- ▶ Monitoring sites are established *after* surveys of land resources are completed to ensure the sites represent well-defined landscape units and systems of land use. This allows results to be extrapolated to other locations with confidence.
- ▶ Complementary programs for monitoring and computer simulation to assess whether soil change can be detected in a reasonable time. Modelling is used to help determine

CONTINENT 1000 km

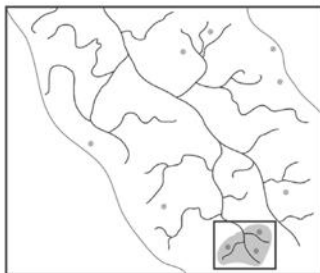
Vulnerable regions predicted

REGION 100 km

Vulnerable landscapes mapped

DISTRICT 10 km

Monitoring sites established in selected landscapes

LOCAL 1 km

Long-term research site located in a typical and vulnerable unit

Mapping	Modelling	Monitoring
• Synthesis • ~1:2 000 000 scale • Broad landscape types and interpreted soil properties • Predict locations of vulnerable regions	• Gross simplification of landscape processes • Broad material budgets • Exploratory analysis	• Proxy monitoring using satellite-based methods (e.g. land cover) supported by synoptic mapping and modeling
• Soil-landscape units • 1:100 000 scale • Delineate vulnerable landscapes • Limited laboratory testing	• Generalised hydrological and simplified farming system modeling • Input data from survey and limited direct measurement • Some capacity for validation from field experiments	• Proxy monitoring of land use and management • Field verification of proxy measures • Survey monitoring feasible • Programs to improve land literacy
• Soil map units • 1:25 000–1:100 000 scale • Most sensitive lands identified to guide location of monitoring sites	• Farming system modelling at enterprise level and hydrological modelling at intermediate catchment scale • Input data from direct measurement • Validation from field experiments	• Simple monitoring • Network of sites for direct measurement of soil change in selected and vulnerable landscapes • Programs to improve land literacy
• Full inventory restricted to the long-term ecological research site • More detailed than 1:10 000 • Intensive field measurement to support experimental program	• Detailed deterministic modelling • Comprehensive validation of models	• Integrated monitoring • Major long-term ecological research site • One of perhaps 20 or so sites in Australia • Direct monitoring of landscape processes

Figure 30.4 Strategy for gathering information on natural resources at various scales

where monitoring sites should be located and how often measurements should be made. Modelling can also be used to extrapolate results from monitoring sites.

- Monitoring is directed to regions where early change is most likely (Vos et al. 2000; Tegler et al. 2001). This avoids wasting resources on measurement programs and it ensures that monitoring provides an early-warning system.

Table 30.2 Checklist of design conditions for a monitoring program (after Jeffers 1978; Usher 1991)

Purpose
☒ Have the objectives of the monitoring program been stated clearly and explicitly? ☒ Does the problem require soil information that can only be provided through monitoring and have other sources of information been fully exploited (e.g. mapping, modelling and narratives)? ☒ Will the information collected during a soil-monitoring program provide valuable scientific information, or input to a decision-making process, or both?
Method
☒ Has a system narrative been prepared for the landscape or regions of interest? ☒ Are there appropriate soil and land resource maps to support all phases of the monitoring program (particularly the design and extrapolation components)? ☒ Are simulation models available for the soil and landscape processes of interest and can they be used to help design the monitoring program? ☒ Can the problem be solved by simple monitoring, survey monitoring, proxy monitoring or integrated monitoring? ☒ Are there aspects of complex behaviour due to factors such as feedback loops, and will integrated monitoring be required to gain sufficient understanding? ☒ Can the process of interest be measured within the requisite time, and are its dynamics either very slow, episodic or controlled by rare events? ☒ What are the most appropriate scales or levels for monitoring the processes of interest, and will measurement at the site level be sufficient to capture trends and allow generalisation to larger areas?
Sampling
☒ Has a comprehensive sampling plan been prepared and documented in a form that will be readily available over the full life of the monitoring program? ☒ Will purposive sampling be used and, if so, are the implications of inevitable bias fully appreciated? ☒ What is the scope of inference of the monitoring program? ☒ What is the target population? ☒ Will the planned sampled population coincide with the target population? ☒ If different combinations of soil, climate and land use are to be monitored, will their status change during the course of the monitoring program? ☒ What is the expected magnitude of spatial and temporal variation in the soil variables being measured and is a pilot study required to design an efficient measurement program? ☒ Will a fixed location or flexible network be used? ☒ Has an unambiguous soil individual been defined and is it large enough to sustain repeated measurement? ☒ Can different operators visit the planned monitoring site at subsequent times and be able to adhere to the original sampling plan (e.g. repeat the stratification of the soil individual both vertically and laterally)? ☒ Are there clear protocols for visiting sites and have precautions (e.g. rules for traffic) been taken to avoid inadvertent disturbance that may affect later measurements? ☒ Are the dynamics of the soil process of interest understood sufficiently to allow specification of the frequency of measurement? ☒ What will be the frequency of measurement and are there issues of timing that require standardising (e.g. time of year, soil water content)? ☒ Will specimens be bulked and, if so, are there clear protocols for mixing and homogenising?

Measurement

- ☒ Has a comprehensive measurement plan been prepared and documented in a form that is readily available over the full life of the monitoring program?
- ☒ Do the soil variables have a direct link to the natural resource management problem or scientific issue being addressed?
- ☒ Can the soil variables of interest be measured accurately and reliably?
- ☒ Can the behaviour of the soil variables be predicted without the need for monitoring?
- ☒ Has the cost of soil measurement been estimated (with the input of a qualified statistician) and is it within the resources of the planned program?
- ☒ Are there sufficient resources to ensure both characterisation of the site and profile, as well as monitoring the particular soil properties of interest?
- ☒ Are there appropriate measurement methods for characterising land management?
- ☒ Are there appropriate measurement methods for characterising relevant environmental variables (e.g. weather, vegetation)?
- ☒ Are the laboratory measurement methods capable of providing the accuracy and precision required by the monitoring program?
- ☒ Are there appropriate laboratory standards to ensure accurate and precise measurement over long periods of time?
- ☒ Does the laboratory participate in inter-laboratory comparisons and quality assurance programs (e.g. under the auspices of the Australian Soil and Plan Analysis Council, ASPAC)?

Archiving

- ☒ Is there a well-organised system for archiving specimens?
- ☒ Is the archival system connected with the data management system?
- ☒ Are the containers and labeling systems adequate?
- ☒ Is the physical environment of the soil archive appropriate for long-term storage?

Data management

- ☒ Has a comprehensive data management plan been prepared and documented in a form that is readily available over the full life of the monitoring program?
- ☒ Is there a system for recording all relevant ancillary data collected during a monitoring program?
- ☒ Is there a system for defining data quality and are records updated and checked on a regular basis?
- ☒ Are there systems for backing up all data?
- ☒ What plans have been made for regular reporting of results?

Analysis

- ☒ Have the methods for statistical analysis been defined and is there a documented plan?
- ☒ Have the hypotheses to be tested in the analysis of the results been defined at the outset?
- ☒ Will the methods of analysis allow the detection of trends, cycles, noise and outliers?
- ☒ Is there access to a qualified statistician's advice and will he or she be available during all phases of the monitoring program?

People and institutions

- ☒ Have individuals and organisations agreed to take responsibility for the monitoring program?
- ☒ Are appropriate staff with sufficient training available for all tasks?
- ☒ Are there plans to cope with staff turnover, technological advances (e.g. computer software) and institutional change?
- ☒ Have reliable funding sources been secured?

Fulfilment

- ☒ Are there rules for stopping the monitoring program or will a regular program of review be required?

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Legal and planning framework

M Capelin

Background to legislation and policy affecting soil and land surveys

The description and classification of soils (and the related land surface of the Earth) is usually carried out to support activities and decisions on land use, land management, resource development and planning, and environmental protection. The body of law relating to soil and land survey has developed around these purposes, so that land and soil information is seen as ensuring outcomes that protect the public interest. Despite that indirect link, there is very limited law relating specifically to the conduct of soil and land surveys as an isolated activity. Legislation rarely specifies standards for land and soil surveys. Most commonly, specifications are set out in guidelines, policies or regulations that support specific planning, development or environmental legislation. For example, legislation setting out processes for environmental protection usually provides for the setting of terms of reference for environmental impact assessment (EIA) that specify the types of natural resource information the proponent must collect, and the standards for information collection that must be carried out in order to determine the environmental impact of a particular development proposal.

This situation is in contrast to the large body of surveying and property law surrounding the description of the location of land in space (cadastre), a concept that is central to defining interests in land, particularly rights and ownership.

The body of law relating to the collection and use of information in general also applies to soil and land information. These laws cover issues such as intellectual property rights, ownership and access to information and due diligence.

Evolution of environmental law

Environmental and planning law has evolved from, initially an emphasis on the common law duty of individuals to protect the interests of other individuals, to the current emphasis on the responsibility of all individuals to protect the values of the natural environment in addition to human welfare.

Common law, developed on the basis of judgements by courts on individual cases, is primarily concerned with the protection of private property rights relating to trespass, nuisance or negligence. Law embodied in legislation, also known as statute law, is passed by Commonwealth and state parliaments and prevails over common law if conflict arises. Laws relating to planning and environment matters have generally extended the principles of common law to protect the common good in general, and the environment, from the actions of individuals.

This has resulted in increasing requirements for decision-making to be based on objective measurement of biophysical, and more recently, socioeconomic data. Soil and land data are one of the sets of biophysical data on which planning and environmental protection decisions, and the resolution of disputes, are based.

Decision-making using soil and land information

Scale of biophysical data and decisions

For decisions on land use and environmental matters, biophysical data are used primarily at two scales.

The first scale is for planning of regions, districts or catchments, where broad identification of issues such as land capability or environmental value is made. At this scale, decisions are made and resources allocated to preferred uses, or resources are protected for specific purposes (e.g. biodiversity conservation). When different interest groups disagree over the intended allocation of an area or resource, resolution of the dispute often occurs at the political level – political measures are used to influence a government decision. It is unusual for legal challenges to arise at this level of decision-making. Accurate data on natural resources for broad planning will contribute to better decisions on resource allocation and fewer disputes; this will in turn minimise subsequent disputes at the more detailed scale.

The second scale is the property or site, where disputes and legal challenges are more common and where biophysical data are more often used for decision-making. Most commonly, decisions and challenges to decisions are made under planning legislation; this gives a planning authority the power to give or refuse approval to use land for a particular purpose or to place conditions on how a use is operated. Although many issues at this level are concerned with community impacts such as traffic, amenity, noise and so on, many issues require information on land suitability, environmental impact and the likely consequences of development or change in land use. Accurate land and other resource information is needed for a proper decision to be made.

Precautionary principle

The precautionary principle states ‘... where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation’ (Bates 2002).

The precautionary principle has become widely accepted as a general principle of environmental policy, law and management. It is a rational approach to uncertainty and justifies action to avoid possible serious or irreversible environmental harm in advance of scientific certainty of such harm. Although an important and intuitively sensible principle, in practice the incorporation of the precautionary principle into law and policy, and its application in practice, have been marked by controversy and confusion (Cooney 2003).

Embodied in the principle is the question of scientific certainty about the natural environment and the consequences of an action on the natural environment. Unfortunately, the principle as defined gives no clear guidance as to what amount of evidence is required before application of the principle is triggered (Bates 2002). While a civil action concerning the likelihood of, and responsibility for, environmental harm would be judged on the basis of the balance of probabilities, scientific judgement, however, normally requires a standard of proof based on a 95% confidence level. In general, the use of data on soil and land in the resolution of planning or environment disputes will usually lack 95% scientific certainty, hence decisions

will commonly be made in the face of a lower level of certainty. To seek the higher level of certainty would elevate the standard of proof to that used in criminal law cases – proof beyond a reasonable doubt.

A practical approach to application of the precautionary principle has been provided by Young (1995):

- when the cost of degradation may be serious or appears irreversible, or there is little prior experience or scientific confidence about the outcome, or both, follow the precautionary principle strictly
- when the cost of degradation may be serious but reversible, maintain a large safety margin and require use of the best available technology
- as confidence with the activity increases, allow a transition to arrangements that only require the use of the best available technology when this does not entail excessive cost
- when the threat of environmental damage is not irreversible, or if irreversible it is not serious, use conventional cost–benefit analysis.

Resource management and the environment

A useful framework for describing the body of policy and law that affects land and soil is to distinguish between the concepts of a resource and the environment. Conacher and Conacher (2000) describe a ‘resource’ as something that is utilitarian and anthropic – that is, a thing is not a resource unless it can be used to fulfil human needs. Hence, land and soil are resources for the purpose of food and fibre production and the support of domestic, industrial and commercial structures. The environment, however, is the set of all things that surround and influence an object or system. In the case of a resource ‘system’, the environment both affects the formation and quality of a resource and is affected by resource utilisation through the assimilation of waste materials and pollutants.

Therefore, it is useful to approach a consideration of resources and the environment through an input–output model. First, natural resources are identified through measurement and subsequently brought into use through a planning and development approval process. Second, ongoing management of the resource is considered as ‘the set of technical, economic and managerial practices which use resources for the purpose of satisfying peoples’ utilitarian needs and wants.’ (Conacher 1978). Third, the effect of resource use on the environment is considered either concurrently or separately during both the planning and the management phases of resource utilisation.

As a result of this approach, law and policy affecting land resource assessment may be considered under the following four headings:

1. land resource assessment
2. planning and development
3. resource management
4. environmental protection.

Legislation on assessment of land resources

There is very little stand-alone legislation covering the conduct of land and soil surveys (Table 31.1). The exception is the *Queensland Soil Survey Act 1929* that sets out powers of entry by authorised soil surveyors conducting government-sponsored surveys on private land to undertake soil survey activities. The Act also provides processes for determining claims for

Table 31.1 Australian legislation on land resource assessment

Jurisdiction	Legislation
Qld	Soil Survey Act 1927

compensation for damages to property arising from negligence in carrying out soil survey activities. However, the Act makes no requirement for surveys to be conducted to a published standard. Although there is provision for the preparation of regulations under the Act, none have been prepared. Other States have these provisions incorporated in related statutes such as soil conservation and catchment management legislation.

Legislation and policy on land use planning

Legislation on land use planning is concerned with allocating land uses on the basis of assessment of land suitability and the evaluation of the ‘best available’ use. Urban land allocation was originally focused on orderly land survey (cadastre) and disposal, with an emphasis on property rights. Later, urban planning was concerned with the provision of public infrastructure for water supply and waste treatment to address public health and welfare concerns. It has only been since the 1950s, with the advent of rapid urban expansion after World War II, that land use planning has seriously addressed the environmental implications of urban settlement and land use patterns.

In Victoria the *Planning and Environment Act 1987* (Table 31.2) incorporates into planning the protection of natural resources, ecological processes and various social and cultural values at state, regional and local levels. Similarly, the *Environment Planning and Assessment Act 1979* in New South Wales incorporated environmental, social and economic objectives achieved through a range of State, regional and local planning policies and plans.

Most jurisdictions adhere to the broad principle of allowing local government the major role in making planning decisions within the constraints set by state policies. There is also general adherence to tiered layers of planning, with strategic plans prepared at regional or local government scales setting out a broad land use pattern that, in turn, is implemented through a strict development control regime at the site or property level. This is achieved by variants of a zoning system: the land use options for a particular lot is determined by the zone or designation applied to a local area. Some planning jurisdictions such as Queensland’s *Integrated Planning Act 1997* have taken a performance-based approach, and this allows a broad range of development possibilities for urban land provided defined performance outcomes can be demonstrated by a development proponent. This approach is promoted as likely to give better flexibility and improved environmental outcomes, but opponents of the approach point to a reduction in certainty and an increase in disputes by proponents and an expensive legal appeal process that favours the developer.

Legislation that controls land use change and development approval by state and local governments generally supports the collection and use of information on land resources in the preparation of planning schemes and the assessment of development applications. It is in the dispute-resolution process before a court or technical tribunal that expert evidence on soil or land matters is often called and used for decision-making.

An overlap between planning and environment protection legislation appears to be growing as jurisdictions seek to ensure that environmental, social and economic impacts of developments are fully considered in the process for approving land use. In several states this has resulted in the integration of legislation on these matters (Table 31.2).

Table 31.2 Australian legislation on land use planning

Jurisdiction	Legislation
Vic	Planning and Environment Act 1987
Qld	Integrated Planning Act 1997 Coastal Management and Protection Act
NSW	Environment Planning and Assessment Act 1979 Local Government Act 1993
NT	Planning Act 1979
ACT	Land (Planning and Environment) Act 1991
SA	Planning and Development Act 1972
Tas	Land Use Planning and Approvals Act 1993 State Policies and Projects Act 1993
WA	Planning Legislation Amendment Act 1996

Legislation and policy on land management

Whereas legislation on land use planning deals with decisions prior to the take up of a new land use or intensification of one, land management legislation is concerned with achieving sustainable management of natural resources to ensure ongoing productivity, protection of ecosystem values and processes, and the avoidance of environmental harm from an ongoing activity. Legislation addressing land management problems has been developed to deal with specific issues such as soil conservation, vegetation management or forest management. It is only in more recent times that more comprehensive legislation dealing with catchment management has attempted to integrate the various elements of natural resource management.

Until very recently, there has been no over-arching natural resource management legislation in Australia equivalent to New Zealand's *Resource Management Act 1991*, which includes planning and development control powers, although Tasmania has a close approximation in its Resource Management Planning system and South Australia passed the *Natural Resources Management Act 2004* (Table 31.3).

Table 31.3 Australian legislation on land management

Jurisdiction	Legislation
NSW	Soil Conservation Act 1938 Native Vegetation Conservation Act 1997 Crown Lands Act 1989 Catchment Management Act 1989 (Catchment Management Committees)
Qld	Soil Conservation Act 1986 Land Act 1994 Vegetation Management Act 1999 Vegetation Management and Other Legislation Amendment Act 2004 Water Act 2000
NT	Soil Conservation and Land Utilization Act NT Soil Conservation and Land Utilization Act 1995 NT Planning Act 2001

(Continued)

Table 31.3 (Continued)

Jurisdiction	Legislation
	NT Pastoral Land Act 1996 NT Water Act 1992 Parks and Wildlife Commission Act 1998 Parks and Wildlife Conservation Act 1988 Commonwealth legislation relevant to the NT includes: Native Title Act 1993 Aboriginal Land Rights Act (NT) 1976 Environment Protection and Biodiversity Conservation Act 1999
SA	Natural Resource Management Act 2004 Soil Conservation and Landcare Act 1989 (Soil Conservation Boards) Catchment Water Management Act 1995 (Catchment Water Management Boards) Pastoral Land Management and Conservation Act 1989 Native Vegetation Act 1991 Crown Lands Act 1929
Vic	Catchment and Land Protection Act 1994 (Catchment Management Authorities) Crown Land (Reserves) Act 1978 Soil and Land Conservation Act 1992 (Land Conservation Districts)
WA	Waterways Conservation Act 1976 (Catchment Management Authorities) Land Administration Act 1997
Tas	Resource Management Planning System

In most states and territories, legislation covering soil conservation and vegetation management includes provisions for the collection of soil and land data for both property and catchment planning, the rationale being one of protecting the soil resource from erosion, ensuring that vegetation removal does not lead to land degradation. With regard to vegetation management, controls over land clearing are based partly on the protection of biodiversity, endangered vegetation types and habitat. In addition, considerations of whether clearing will be permitted include the implications for salinity, soil erosion and subsequent sustainability of land use. In most jurisdictions there are regional and catchment planning processes that rely on land and soil data to identify areas prone to degradation and sites suitable for potential development.

Legislation covering the management and administration of state-owned land obliges holders of leases and trustees of reserves to practice sustainable land management. This is achieved through prescriptive land allocation processes: the most appropriate use for areas of state land is determined and lease conditions are imposed on land managers that are monitored to varying degrees by state land administration agencies. In recent years, a more performance-based regime has been adopted by agencies; targets for land condition are set and both onsite monitoring and remote sensing are used to measure progress towards these targets.

The target-setting approach has been further refined in the recent move towards devolving more responsibility for resource management to regional bodies and boards. The trend has accelerated since 2000 with the creation of the National Action Plan for Salinity and Water Quality and the Natural Heritage Trust. Here, to guide the investment of funds, the Australian government funded regional bodies (with matching state funding) to prepare plans that incorporate targets for management of natural resources. Many of these local boards have grown from the original soil conservation district boards or catchment boards and carry responsibility

Table 31.4 Australian legislation on environment protection

Jurisdiction	Legislation
Commonwealth	Environment Protection and Biodiversity Conservation Act 1999
NSW	Environmental Planning and Assessment Act 1979 Protection of the Environment Operations Act 1997
NT	Environmental Assessment Act 1982 Waste Management and Pollution Control Act 1999
ACT	Environment Protection Act 1997
QLD	Environment Protection Act 1994 State Development and Public Works Organisation Act 1971
SA	Environment Protection Act 1993 Development (Major Development Assessment) Act 1996
Tas	Environmental Management and Pollution Control Act 1994
WA	Environmental Protection Act 1971
Vic	Environment Protection Act 1970 Environmental Effects Act 1978

for implementing sustainable land management strategies and practices. A hierarchy of bodies for managing natural resources is now emerging from these regional bodies in the form of umbrella organisations supporting catchment groups. At the local level, Landcare and other like-minded community bodies continue to operate with funding allocated from the regional level. In some states such as New South Wales, these regional bodies are being asked to carry out some statutory roles regarding vegetation and water management, while in others such as Queensland, the role of regional bodies focus on planning and fund management.

Legislation and policy on environment protection

Environment legislation generally establishes broad frameworks for the assessment of environmental impact of major development proposals (Table 31.4); however, institutional arrangements, assessment conditions and legislative requirements vary between jurisdictions. Most early legislative reform in environmental protection introduced procedures for EIA as an independent process; however, more recent reforms have seen this function merged with more general planning and development assessment powers in planning legislation.

These frameworks usually provide processes for the examination of any activity that has the potential to cause damage to the quality of people's environment or affect their comfort or health, particularly through air, water and noise pollution (Conacher and Conacher 2000). The legislation usually incorporates principles of ecologically sustainable development, broadly consistent EIA processes, powers to develop policies for environment protection, support for self-regulation, and licensing and other regulatory arrangements. The standard EIA processes include:

- a requirement for a 'notice of intent' or preliminary advice outlining the proposal
- the preparation of terms of reference for individual assessments of projected impact; production of an environmental impact statement (EIS)
- consideration of mitigation measures
- approval processes that involve the setting of conditions to safeguard environmental values.

The EIS stage also involves the production of a draft EIS that is subject to consideration by government agencies and the public. A final, revised document is then prepared by the proponent and used by the consent authority to make a decision.

Bates (2002) suggests that an effective system for EIA should encourage professional competency in the preparation, assessment, reporting, storage and retrieval of data; should maximise public participation; and should provide an avenue for, of redress of, inadequately prepared statements. Although EIA is one of the major sources of scientific input into environmental decision-making, scientists themselves are often sceptical of the process because of lack of adequate research and on-going monitoring (Bates 2002).

State of Environment reporting, requiring reports at the Australian Government, state and territory levels every 3–5 years, has also developed as a means of monitoring the rate of environmental decline (or repair) based on available biophysical data.

Australian Standards

Many professional and industry bodies establish agreed methods for technical processes through the preparation and adoption of a standard under the approval of Standards Australia (AS) (Table 31.5). Standards Australia is the trading name of Standards Australia International Limited, a company limited by guarantee. It is an independent, non-government organisation recognised by the Australian Government as the peak non-government standards organisation for the nation.

Through its committee structure, Standards Australia develops and maintains more than 7000 Australian Standards and related publications. These documents are prepared by 1500 committees involving more than 9000 committee members. The Standards are the common denominator in countless daily business transactions, facilitating trade between individuals, corporations and nations.

A Standard is defined as a published document that sets out specifications and procedures designed to ensure that a material, product, method or service, is fit for its purpose, and consistently performs in the way it was intended to. Thus, standards establish a common language that defines quality and establishes safety criteria. Some obvious examples of standards include those for measuring distance, time, mass and design of traffic lights. Examples of a lack of standards are, on a national scale, Australian rail gauges, and internationally, electrical plugs.

The process for the preparation of a Standard is clearly and rigorously defined by Standards Australia in nine steps.

Table 31.5 Published standards on land and soil matters

Standard	Description	No. of Standards
AS 1289 (.0–.7)	Methods of testing soils for engineering purposes	81
AS 4419	Soils for landscaping and garden use	1
AS 4439 (.1–.3)	Wastes, sediments and contaminated soils – preparation of leachates	3
AS 4454	Composts, soil conditioners and mulches	1
AS 4479 (.1–.4)	Analysis of soils	4
AS 4482 (.1–.2)	Guide to the sampling and investigation of potentially contaminated soil	2
AS 4764	Guidelines for validation procedures for chemical analysis of agricultural and contaminated soil	1
AS/NZS 4584	Geographic information – Australian and New Zealand land use codes	1

1. Request for a Standard by an industry or government or professional body.
2. Project approved by the appropriate Technical Committee and Standards Sector Board.
3. Formation of a Technical Committee (supported by a Standards Australia Project Manager as secretary) as a process manager.
4. Preparation of a preliminary draft Australian Standard.
5. Preparation of a Committee draft Australian Standard.
6. Draft published for public comment for two or three months.
7. Consideration of comments by the Technical Committee.
8. Draft Standard subject to postal ballot by the Technical Committee.
9. Approval by the relevant Standards Sector Board on behalf of the Council of Standards Australia.

The Technical Committee reviews published Standards from time to time – at least within 10 years of their publication for most Standards and within 7 years for Standards subject to rapid change in practice or development.

Standards are not legal documents in themselves, but many are called upon in state or Commonwealth legislation, thus making some of them mandatory. The remainder are adopted by industries as voluntary standards.

There are at least 94 Standards relating to soil and land matters. There are no Standards published concerning the survey of soil or land. The 94 are dominated by 81 Standards covering methods for testing the engineering properties of soils for the building and construction industry. Of the remainder, most are concerned with analysis of potentially contaminated soils or soil composition for the landscaping and amenity nursery industries. There is one Standard covering the use of land use codes for the mapping of land uses in Australia and New Zealand.

Legal obligations associated with land and soil survey and use of data

Due diligence

Any soil or land resource surveyor undertaking professional work accepts the ordinary liabilities of any person who follows a skilled calling. Such a person is bound to exercise due care, skill and diligence in their work practices.

The expression ‘due diligence’ has its origins in several disparate ideas that coalesce in the observance of a certain standard of conduct in dealings between parties. At the heart of this conduct is the absence of negligence.

In exercising due diligence the person is not required to have an extraordinary degree of skill or the highest professional attainments but must bring to their work the competence and skill that is usual among, for example, soil surveyors practising their profession (Duncan and Travers 1995).

What is all-important in determining a claim of damage is the nature of the engagement and the task undertaken. It may not satisfactorily answer a claim for negligence against a professional to say that general practice was followed in the circumstances. The existence of professional standards such as those set out in the *Australian Soil and Land Survey Handbook* series or the existence of a published Australian or International Standard provides a reference. However, it is the professional’s responsibility to keep adequate records to demonstrate that recognised standards have been applied to the work in dispute. Although a professional soil or land surveyor may make use of the skills of others in the performance of duties, these employees or contractors must be properly supervised (Duncan and Travers 1995).

Duty of care

An individual's common law duty of care is to take all reasonable and practical measures to avoid causing foreseeable harm to another person's land or their use or enjoyment of that land. However, the common law duty of care does not prevent individuals from causing damage to their own property. The law assumes that market forces and common sense would prevent this.

A breach of the common law duty of care is through an individual's negligence to:

- be careful in their actions
- adequately assess the risk, likelihood or degree of potential damage
- prevent a foreseeable consequence of their actions.

The measure of a breach of the common law duty of care depends on the particular circumstances. A key consideration is what available knowledge exists that would allow the individual to understand the foreseeable consequences of their actions. These consequences may be well understood by government and scientists through research findings that produce specialised knowledge and skill. However, the degree of understanding of this knowledge and skill in the community, and by a particular individual, will depend on the education and awareness activities conducted by government or industry.

Any assessment of this knowledge should be based on the contemporary state of knowledge. For example, an individual clearing trees in the 1960s with permission from the government of the day could not be in breach of their duty of care if this was later shown to cause salinity on a neighbour's property. However, the same activities in 2007 may be a breach if the consequences are well known, foreseeable and preventable.

The statutory duty of care in, for example, Queensland's *Land Act 1994* places a duty on all holders of leases, licences and permits to care for the land under their control. Hence the statutory duty of care is an addition to the common law duty in requiring the landholder to use all reasonable and practical measures to avoid causing foreseeable harm to the land under their control.

As for the common law duty of care, a measure of a breach of the statutory duty of care on grazing land would depend on what is the commonly understood knowledge of grazing land management practices (in particular, their effect on land resources) and the access that a land manager would be expected to have to this knowledge. The role of land resource surveys, the content of published reports and their availability to persons responsible for resource management are important elements in the adoption and uptake of the duty of care and in any assessment of whether an individual has discharged their duty.

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Communication

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Introduction

This chapter provides a guide to how to communicate land resource information using a broad spectrum of methods. The traditional map and report from a survey do not adequately convey the wealth of information gathered. Beckett and Bie (1978) document many of these limitations and comment that users often find the actual surveyor to be of more use than the map and report. At the same time, revolutions in communication technology provide solutions to many problems, particularly with widespread broadband access to the Internet.

Market research in New South Wales (Polymex 1998) indicated that many land managers and planners were aware of soil–landscape maps and reports. Awareness of these products had come through word-of-mouth. However, many groups with an influence on land and water management were either unaware of the maps or reports, or had only a limited appreciation of their value.

It seems essential, therefore, to publicise the availability and potential use of information to a broad audience. Survey groups need to develop more diverse and effective communication methods. A good starting point is effectively delivered information tailored to meet the needs of particular users. General information, broadly delivered, while sometimes valuable will not usually meet the needs of resource managers tackling specific problems.

Planning

Effective communication helps maximise the benefits gained from what has usually been a long and costly exercise. Therefore, earmark sufficient resources for communication at the start of a survey. You will need a plan. It doesn't work to treat communication as a haphazard or token activity at the end of a survey.

The components of the communication plan are outlined in this chapter. Messages need to be delivered in an understandable way and since communication is a two-way process, room has to be made for acknowledgement that the message has been received. The main goal is transferring expert knowledge so that planning and management of land is improved. Always remember that the value of information depends largely on whether it might change a decision-maker's choices.

Objectives

In terms of justifying communication expenditure, quantifiable objectives for the communication plan can be used to assess the success of your communication efforts. In essence, the objectives should identify target audiences, timeframes and expected outcomes.

Target audiences

The target audiences for general-purpose surveys are diverse and often difficult to define at the outset. Thus the difficulty is compounded by experience, which shows that information can turn out to have totally unexpected ramifications. The subject is discussed in more detail (see *Identifying the target audience*).

Timeframes

Communicate with target audiences during the project and not just at the end. At the beginning, raise awareness of the project and inform key stakeholders and potential users of the survey and its goals. Use workshops, structured interviews, and printed material for promotion. Progressively develop products and ensure plenty of opportunities for feedback. The following is an example:

- ▶ Stage 1: Provide a draft map of land units or soil classes for Landcare groups and scientists to review.
- ▶ Stage 2: Supply a finalised map in an accessible format (e.g. compact disk showing soil classes, land suitability, management hazards, and resource limitations). This product is for general use but aimed specifically towards extension officers.
- ▶ Stage 3: Release a resource manual for the study area, and establish a website. These products are primarily aimed towards extension officers, land managers and planners.

Expected outcomes

Have a good understanding of your expected outcomes. Sage (1990) distinguishes between action-oriented communication (which expects a response or dialogue with the target audience), and more passive communication (i.e. simple delivery). The latter raises awareness, without necessarily changing attitudes and behaviour. Action-oriented communication involves a purposeful dialogue (e.g. demonstrating the benefits of a certain land management on a particular type of land). It aims to reshape thoughts and behaviour to achieve change. While this is often desired, the time and effort behind it can be substantial.

Identifying the target audience

Notwithstanding the difficulties raised earlier, be as clear as you can about the target audience. Is it a broadly defined group or more specific? The latter may include people who readily participate in extension activities or who will directly apply results from the study, such as the agency commissioning the survey. The agency may have a specific purpose in mind, but consider whether this purpose can be broadened to cater for a much wider audience.

It helps to identify the change in behaviour the project is seeking to achieve. Understand the audience in terms of their technical sophistication and capacity to take in information. If your team is unclear on the message to be delivered and the goal to be achieved, then the communication will most likely fail (Sage 1990). The target audience needs to understand the messages and be motivated by them. There will often be a balance between what the audience wants to know as well as what they need to know. The tension often becomes evident when surveys identify serious hazards (e.g. salinity, erosion) and propose remedies. You may need to measure the attitudes and behaviour of a target audience through market surveys.

It is useful to prepare a table showing the client categories and their information requirements. The latter should address the type of data (e.g. primary data versus interpretations at various levels), optimal scale, and timeframes for delivery. Consider both short-term and long-term needs and ensure that expectations are realistic.

Messages to deliver and desired response

Involve the target audience in the project from the start as this ensures their ownership and participation. Forming a focus group from the interested parties is often worthwhile. List the responses that you are seeking from each party. Examples of desired responses could be:

- a raised awareness and understanding of soils in a region
- a willingness to use the information for soil management
- a willingness to invest in the survey.

Structure the delivery of information in the light of this feedback. Know what is important to your audience and understand their expectations – it is very easy to over-inflate expectations at the start of a project. You will also need to be clear about the cooperation that you require (e.g. access to land, history of land management).

In most cases the target audience will want information from a survey in order to help them do their job better. Make information easy to find and understand.

Successful communication depends heavily on the credibility of the communicator. Credibility at the start of a survey largely depends on association with a reputable organisation and it will be enhanced when:

- project staff are genuinely interested in the needs of clients
- project staff exhibit a high level of technical proficiency
- results are expressed in an interesting and understandable form
- results provide a better basis for decisions on planning and management of land.

Actions and techniques

Use the communication plan to define how information will be transferred. Mechanisms include the following:

- ▶ *Impersonal*: publications (maps, reports, manuals), static displays (posters, monoliths), videos, CDs, brochures, stickers and slogans, posters, magazine articles, and press releases for newspapers, radio and television.
- ▶ *Personal*: forums, field days, seminars, training courses, telephone interviews, one-on-one discussion.

Interim products provide a good vehicle for communication. A website with an email address is useful, as are drafts of maps and land management reports. Field days during the course of a project are good for generating feedback. They also promote awareness and understanding of the survey prior to the release of final products.

Barriers to effective communication

Identify potential barriers to effective communication, along with possible remedies. Some common examples between the end users and the product are listed in Table 32.1.

Communication with or within interdisciplinary teams

Interdisciplinary teams cannot function without effective communication. This is too large a subject to consider here, although two particularly important aspects are worth mentioning. First, certain concepts and terminology of land evaluation (jargon) can quickly irritate other specialists (see van Diepen et al. 1991) or cause unnecessary confusion. Team members need a good understanding of the perspectives of each other's discipline.

Table 32.1 Barriers to effective communication and possible remedies

Barriers	Examples of remedies
Users do not know how decisions affect land, or they do not appreciate biophysical constraints	Improve land literacy
	Promote the use of information on land resources among potential users via more active methods (e.g. sending out land resource information with conveyancing papers)
Users do not know where to find information	Exploit the Internet
Users cannot translate the information into a form relevant to management (e.g. 'Can I grow this crop here?')	Understand the management question. Prepare interpreted maps with the right level of detail
Users do not trust the accuracy of the information (e.g. 'How certain can I be that the map is correct?')	Presentation of data quality and uncertainty measures

The second and related aspect concerns the often ineffective communication between field-based surveyors and simulation modellers. Make sure the two groups understand each other's technical requirements (e.g. simulation modellers can usefully undertake functional sensitivity analysis to define the accuracy and precision of information that field surveyors need to supply).

Conflict resolution and mediation

Information on land resources can be valuable for reducing conflicts over land use. A good example is the SIRO-MED system presented by Cocks et al. (1995). The system allows stakeholders involved in planning for forestry (e.g. loggers, foresters, conservationists, government agencies, local government) to have access to a geographical information system (GIS) with supporting models and expert opinion. The information system is used to produce a range of plans for land use that reflect the values and priorities of stakeholders. If stakeholders are willing, the plans can be modified systematically and rapidly. This allows them to explore new options, understand alternative views and engage in informed mediation. Of course, reliable land resource information is only one input to SIRO-MED. The approach has widespread potential.

Ad hoc communication

Much of the surveyor's time is spent answering *ad hoc* queries about land and its management. For example, in New South Wales experienced soil surveyors spend around half their time dealing with such queries. The efficiency of dealing with these queries can be improved by providing self-help systems so the public can find appropriate information themselves. Many potential users of survey information may be unaware of the existence of maps or reports. Providing information directly, or providing details about how to access it, is now becoming more common using the Internet. The Victorian Resources Online website (VRO 2006), for example, has a 'Soil and Land Survey Directory' that can be used to search for surveys that have been completed in a region and links are provided to downloadable reports.

Legal issues

Information from surveys is not infrequently used in litigation. During planning, make sure appropriate disclaimers, aspects relating to resolution and reliability, and statements concerning recommended uses of the information, are clearly displayed for all products. See the ASRIS website for examples of disclaimers (ASRIS 2006).

Technical information and jargon

Avoid jargon whenever possible and consider producing both a scientific report and a plain-English version to suit the target audience (Gunn and Reid 1988). Some form of soil classification is usually needed and it is central to conventional survey. Unfamiliar names and foreign concepts in a classification system form barriers to communication. A possible solution is to give an appropriate level of classificatory detail but provide supporting guidance on local, vernacular soil groupings along with some form of translation. Several regional classification systems have been developed in Australia to improve communication (Fitzpatrick et al. 2003, see *Chapter 19*). For example, the Soil Groups of Western Australia (Schoknecht 1997) were formulated during mapping programs of the state's agricultural and rangeland regions. The Soil Groups rely on simplified terms (e.g. red sandy earth, grey shallow sandy duplex) and have gained widespread acceptance, especially in regions where soil information was limited or incomplete.

Allocations at higher levels (less detailed) in the Australian Soil Classification (Isbell 2002) are useful at field days. Landholders who previously referred to their soils as 'red soils' and 'grey soils' can readily refer to 'Red Sodosols' and 'Grey Vertosols', especially when explanations and demonstrations are given of the sodic nature of the 'red soils' and the vertic properties of the 'grey soils'. If terminology can be used within a management-related framework, then it is more likely to be accepted.

Simple flow charts can show the logic used to determine soil classes or recommended options for land use. This is a more visual form of communication and it can incorporate photographs, images and diagrams.

Illustrated glossaries are also useful. A glossary specific to a report is good but its compilation is time-consuming. This is also the case on websites where hyperlinks lead from terms to glossaries. Generic glossaries relevant to survey are being compiled and can be edited for the specific purpose: for example, the VRO (2006) website has soil, landform and vegetation glossaries that are periodically updated. These provide definitions and supporting diagrams and images.

Be careful in providing interpretive maps and related information to decision-makers. Gain agreement on the level of interpretation beforehand. Information on land suitability can be provided, but explain how the interpretations were developed. Other recommendations on land use, such as stocking rates, rehabilitation requirements for degraded land, trafficability and fertiliser requirements, can be presented in a several ways but always with circumspection. Make sure provisos, riders or qualifiers are accurate, especially when presenting highly interpreted information.

Examples of communication planning

Queensland Land Management Manuals

Aims

Easy-to-use manuals were required by a variety of groups including planners, consultants, Landcare groups and extension staff (Thwaites 1992), all with an interest in the cropping lands of Queensland. The manuals aimed to:

- identify appropriate land units
- describe all limitations to land use
- document techniques for the best management of different land
- publish results and recommendations in accessible and useable forms
- extend the information to provide training and evaluation.

Objectives

The primary objectives of the program were to:

- provide information for farm planning by supplying maps of land resources for each district along with with a local soil classification
- provide information on soil and land management with an emphasis on limitations to land use, preferred systems for land conservation, and agronomic options
- publish this information in simple, attractive and accessible formats for a wide variety of readers (primarily landholders, Landcare groups, local planners, extension staff and consultants)
- provide clear and accurate descriptions and interpretations of the common soil types in each district in a style suited for field use and which could be easily updated
- aid adoption of the information through workshops and field days with user groups
- enhance existing information and promote its use.

Outcomes

The primary outcomes were to:

- increase awareness and understanding of soils, land types, and issues of land management
- increase adoption of better practices of land management to reduce the risk of degradation and at the same time sustain productivity
- use information on land resources for planning at the strategic, regional and property scale.

Target audience

As an example, the target audience for the Waggamba Shire Land Management Manual (Thwaites and Macnish 1991) comprised:

- the 450 landholders in the Shire
- private and public extension officers in the local district
- Shire Council staff
- agribusiness.

Manuals were designed to encourage self-help. They were aimed at individuals considered innovators and early adopters of ideas within local Landcare groups. The assumption was that these individuals would encourage the adoption of new information or innovation by other, more deliberative or sceptical members of the community.

Response sought

The aim was for information on land resources to be widely understood and applicable to land management.

Messages to deliver

The manuals aimed to convey four main messages.

- ▶ Management of the land resource is critical to sustainable agriculture.
- ▶ Soil is not a 'black box'. Everyone can identify and express its characteristics adequately and be able to use this information in a manner beneficial to the land resource as well as the agricultural system.
- ▶ Options for land use are generated and constrained by land characteristics.
- ▶ Only sustainable options for land use can be recommended.

Actions

Preparation of manuals

A typical manual had three sections held together in a ring-binder:

1. Resource information document – outlining district, climate, geology, land resources, soil classification, land use and recommendations on future land use.
2. Field manual – containing summary information on soil types along with colour photographs of soil profiles and landscapes on laminated cards. Additional information was provided on land suitability, recommended land management and conservation measures.
3. High quality map – the full-colour map depicted land resource areas at a scale of 1:100 000 and was attached in a plastic wallet.

For the Waggamba Shire Manual, the local Waggamba Landcare Group also produced their own section that included experiences and knowledge from long-term and respected residents and land managers in the district.

Field days

The manuals were part of an experiential process of learning. The program also involved field days and workshops to explain how to use the manual. These were designed to help de-mystify some of the more theoretical concepts about soils and land use.

Evaluation

An independent opinion survey was completed for the Waggamba Shire Manual to assess community acceptance. This involved a telephone questionnaire surveying a random sample of 88 landholders in the shire. The most favoured aspects of the package were considered to be the Agricultural Management Unit (AMU) photograph and summary cards, followed by the crop suitability information, the land conservation guidelines and the glossary. The field days proved very popular and discussions around soil pits were considered particularly useful. Most landholders viewed the manual not only as a general reference text, but also as a valuable communication tool between themselves and extension officers. Incidentally, several improvements for future manuals were suggested. A key lesson learned from this exercise was that meeting with members of the local community (Landcare and other community groups) to disseminate information can provide social and ongoing communication benefits at minimal financial cost.

A more formal evaluation of the program to ascertain its effectiveness was undertaken by Noble (1996). This report confirmed the worth of the concept. Manuals were demonstrated to increase knowledge and understanding about soils and land resources; in turn this led to increased awareness about current land management practices and opened the way for adopting improved practices. It also became apparent that maps of land resources are still poorly comprehended by most users. Greater attention to visual depiction of land resource information is necessary. The concept of grouping soil associations (or soil profile classes) into management units also needed to be more widely understood – a simpler and clearer explanation of the concept is required. Another perceived gap was for the survey and assessment methods to be made explicit. This would aid comprehension and add credibility to the resulting land resource information.

The combination of field manuals and soil pit field days was considered to be a very effective extension and educational process and it could be further improved by a series of regular training workshops. Another advance would be to make the manual accessible on a website or CD.

Acid sulfate soils in New South Wales

The second example, acid sulfate soils in New South Wales, was part of a government initiative that was politically sensitive and relevant to many stakeholders. In 1995 a series of risk maps showing acid sulfate soils was prepared for the entire coastline of New South Wales; they covered 126 map sheets at a scale of 1:25 000. During the course of mapping, media exposure increased, the topic received television, newspaper and radio coverage, and acid sulfate soils became a political issue during the state election. The relevant state agency expected a strong reaction to the maps because the presence of acid sulfate soils has the potential to affect coastal development and the economic impact can be large. Consequently, the agency prepared a publicity campaign to coincide with the launch in 1997. This campaign included:

- a well-defined theme ('acid sulfate soils are manageable')
- media briefings by staff that carefully explained in plain English the scientific evidence and potential effects of disturbing acid sulfate soils
- testing of formats for maps and reports (with special attention given to map disclaimers and edge-matching); limited numbers of maps were initially printed for crucial stakeholders and for display at government offices
- efficient methods for people to order and receive sets of maps as soon as possible after release
- preparation and distribution of question-and-answer sheets about risk mapping for the media and general public
- a synchronised release of technical guidelines on acid sulfate soils
- an official public launch with a large contingent of media that resulted in television footage of the Director General in the field at a large acid sulfate scald and the Minister at another site.

On the day of the launch, all Sydney newspapers carried front-page headlines relating to acid sulfate soils. Aspects of the launch including the Minister's sound grab, were included on television and radio news. The official launch was followed by a series of 10 regional information sessions during the following two weeks, with two teams providing similar presentations at different locations using identical resource materials. During the release period, soil surveyors gave more than 20 radio interviews, seven local television news interviews, and 80 presentations to groups of from 20 to 110 people.

Because the communication was clear and logical, there was general acceptance of the risk maps and very little opposition to their release. Preparation of the maps themselves cost around A\$250 000, and a further A\$150 000 was spent on communication.

Guidelines for survey reporting

Principles of survey reporting

Adopting consistent styles of presentation and nomenclature will promote better understanding of information on land resources. Standard definitions are fundamental (e.g. this volume, McDonald et al. 1990; Isbell 2002). Key components of survey reports are outlined in this chapter, although it is difficult to be prescriptive because survey purposes vary, and it is common for land resource assessment to have many uses beyond those initially required or intended. For example, some survey reports are still useful decades after publication (e.g. Gibbons and Downes 1964; Gunn et al. 1967), and serve as historic records that can be used to assist in tracking changes in land condition.

Report guidelines

Report identification, data management and metadata details

Each report benefits from the following.

- Inclusion of a full citation statement, with an explanation of how the report should be referenced.
- Creation of a project code that acts as a unique identifier – this should link to readily available metadata records and a computer file. The format adopted in the Australian Soil Resource Information System is a good default (see McKenzie et al. 2005)
- Provision of a copy of the metadata record (see *Chapter 25*) – this may also serve as an abstract or executive summary. The record includes brief statements on the purpose, amount and type of primary data collected, site locations, scale and resolution, main findings and a listing of derivative products, their identifiers and arrangements for access
- a statement on the quality of the data and how it should be used.

Many users trace information via library cataloguing systems. Ensure library abstracting services have the necessary information. Establish a website containing summary information, notify relevant search engines, and establish links to related sites.

Each project should have an identified data custodian. Data custodians are responsible for the long-term access, security and maintenance of data sets and associated products. With electronic publication updates are easy to arrange, but to prevent confusion all products and their unique identifiers should include version and edition numbers, along with a history of changes and updates.

Descriptions of land units

If certain land units are to be highlighted in the text, focus first on their distinctive features and distinguish them clearly from other units in the same report. Provide readers with a clear mental picture of each land-unit type. Enumerate features that are constant and those that vary or repeat across the map area. These provide hooks for explicit description of the qualities of the land, its suitability for various uses, and potential strategies for management.

Much of the information from a study can be provided to decision-makers in tables but it is often difficult to digest in this form. Use a variety of methods and provide text descriptions as well as block diagrams, photographs and cross-sections (Figures 32.1 and 32.2, and Figure 32.3, Plate 3, p. 421).

Remember that most map units and related interpretations are predictions based on limited field sampling and measurement. Ensure the map user is aware of these and other limits of map interpretation. The map is vital but it is only one tool for conveying information on land resources.

Statistics concerning map units can be derived from environmental data sets for climate (e.g. rainfall, evaporation), terrain (e.g. slope, relief) and land use (e.g. areal percentages for each land use or management system). Box plots, graphs and summary statistics are appropriate (see *Chapter 20*).

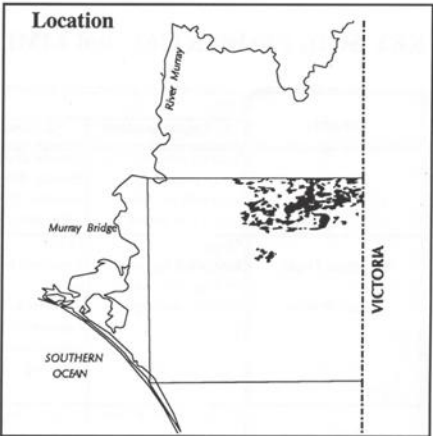
In some cases, soil variation within land units relates to landscape features that can be readily observed. In these instances, explain where in the landscape such features occur. Land units may have to be described in terms of finer-scale unmapped components. These unmapped units can be distinguished according to a set of attributes derived from other data sets (e.g. areas of abundant rock outcrop and shallow soils may be discriminated within a land unit using terrain variables from a digital elevation model). Make sure the rules for defining the unmapped land units are explicit and that areal percentages are presented.

17. KEKWICK SYSTEM

LANDSCAPE DESCRIPTION

Scattered dunefield of predominantly high jumbled to parabolic sandhills and small interdunal flats.

Altitude	: 60-120m above sea level
Relief	: 5-50m
Area	: 65,000 ha
Rainfall	
Mean	: 290-345mm
Apr-Oct	: 190-240mm



NATIVE VEGETATION

Mid dense mallee vegetation on the flats (*Eucalyptus socialis*, *E. foecunda*, *E. incrassata*, *E. dumosa*, *E. oleosa*) and mid dense to sparse on the sandhills (*E. incrassata*). A sparse to mid dense understorey includes *Melaleuca lanceolata*, *M. acuminata*, *M. uncinata*, *Callitris verrucosa*, *Leptospermum coriaceum*, *L. viscidum*, *Casuarina muelleriana*, *Acacia spinescens*, *Baeckea* spp. A tussock shrub stratum (*Triodia irritans*) occurs in places.

CURRENT LAND USE

The sandhills and sandy flats of this system are unsuitable for farming because they are very susceptible to wind erosion, infertile and unproductive. Cropping on the few areas which have, regrettably, been cleared in the past is confined to rye, or perhaps barley, to maintain soil cover and stability with minimum cultivation. Intervening annual volunteer pastures are unproductive and support only occasional strategic grazing depending on seasonal conditions. Lucerne, primrose and veldt grass offer a perennial alternative but can be difficult to establish and maintain.

Geological cross-section diagram (not to scale).

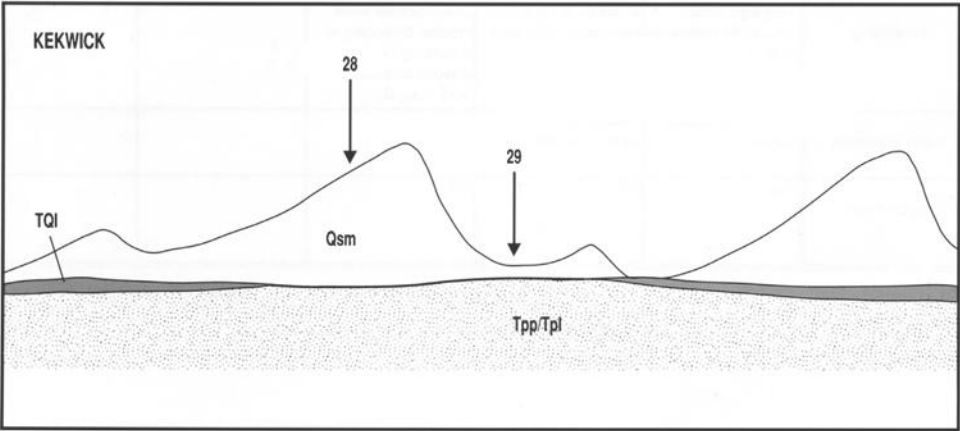
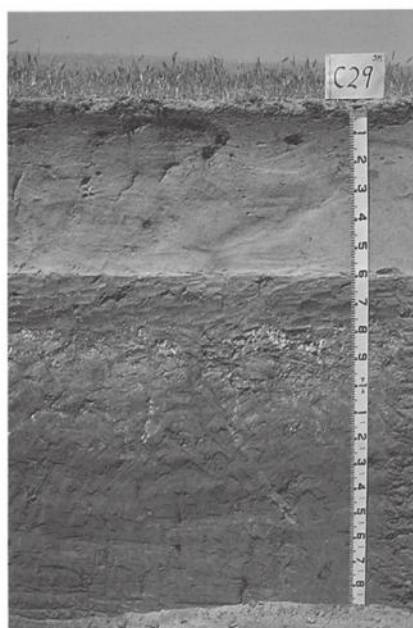


Figure 32.1 (a) Graphical elements associated with land systems can include text (e.g. landscape description), maps and diagrams.

17. KEKWICK SYSTEM

SOIL PROFILE DESCRIPTIONS



Facet 3 : (Proportion=20%) **Sandy flats**

Land Class : 2,3 (a & u,n,m)

Type Profile : C29

Depth (cm)	Texture	Colour	Section: 114			Geology
			Hundred: Cotton	Carbonate	pH (H ₂ O)	
			(%)			
0-9	S	10R 4/3	<1	7.0	Qsm	
9-15	S	10R 4/4	1	7.1	Qsm	
15-57	S	10YR 6/4	<1	7.7	Qsm	
57-60	S	10YR 6.5/4	<1	8.3	Qsm	
60-67	SCL (F1)	7.5YR 5/6	<1	9.5	Tpp	
67-77	SC	5YR 4/8	1	9.6	Tpp	
77-95	SC	5YR 4/8	4	9.8	Tpp	
95-115	LC	5YR 4/8	3	10.0	Tpp	
115-180	SCL	5YR 4/8	<1	9.1	Tpp	
180-190	SCL	5YR 4/8	<1	5.7	Tpp	

Soil Classification

[Australian]

Bleached ◊, Calcic, Brown CHROMOSOL;
thick, non-gravelly, sandy/clayey, moderate

[Soil Taxonomy]

fine, mixed, thermic
ARENIC PALEXERALFS

**Kekwick landscape north-west of Kulkami
(Section 122, Hundred of Cotton).**



Figure 32.1 (b) Graphical elements associated with land systems can also include photographs, such as those of soil profiles and landscapes (McCord 1995).

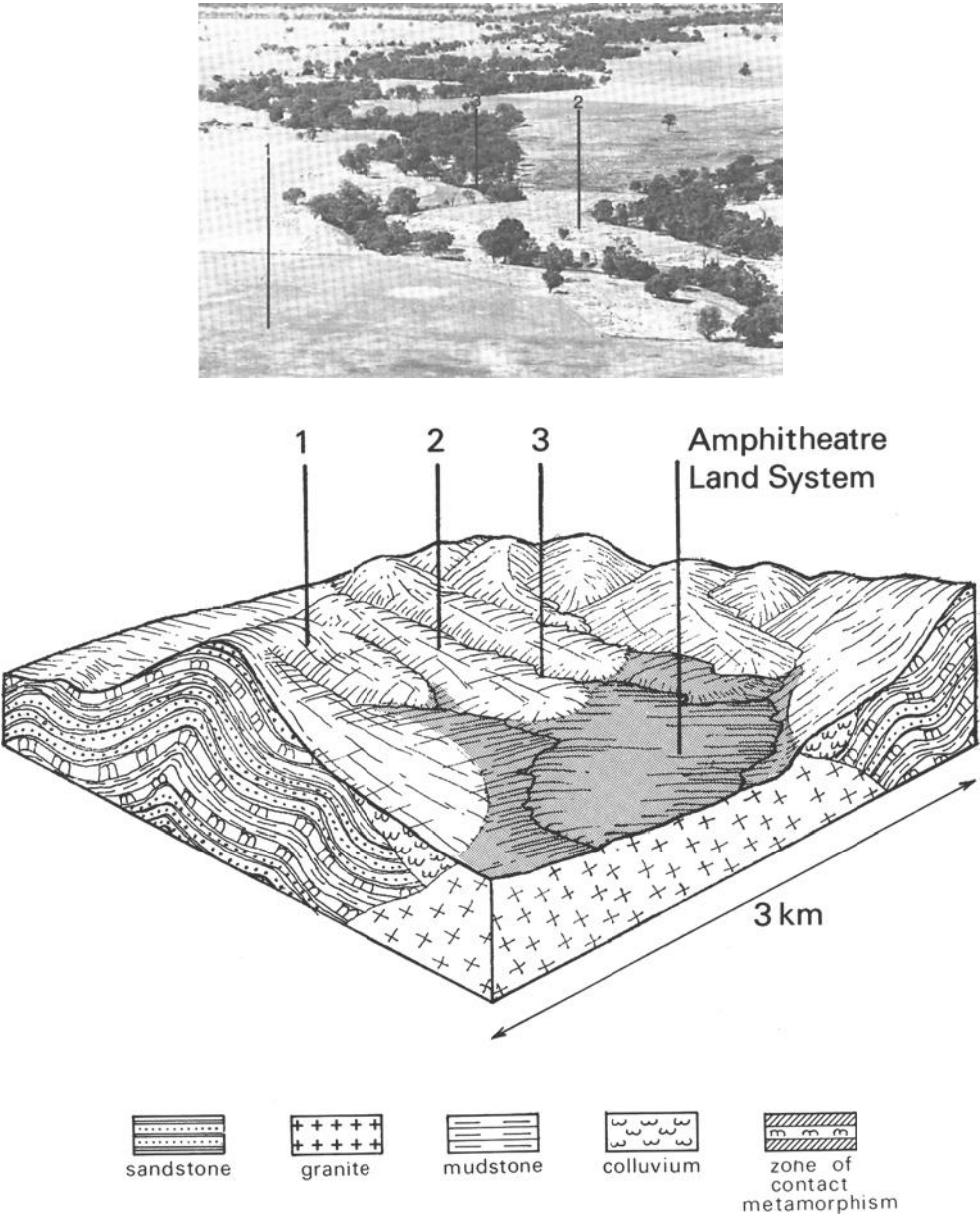


Figure 32.2 (a) Oblique aerial photographs and (b) matching block diagrams can be used to highlight features of the landscape. Lines 1, 2 and 3 indicate separate land units.

Soil profile descriptions

Soil profile descriptions are an important part of a land resource survey but the standard terms in McDonald et al. (1990) can be intimidating to users. Several plain-English formats are available (NSW Department of Natural Resources 2006). Use images of soil profiles wherever possible. Depth functions and graphs depicting changes in soil properties down the profile can be effective (e.g. McKenzie et al. 2004).

Maps

Format and user requirements

Maps are an integral part of any land resource assessment so obtain advice from a cartographer. Catalogues of high-quality maps (e.g. the annual publication from ESRI) are an excellent resource for developing map formats to suit various clients. Eswaran et al. (1981) identified four factors influencing both legibility and understanding:

1. the number of land units delineated
2. the choice of colours and patterns used to represent these units
3. supporting locational detail
4. quality of cartography and map layout.

There are other considerations, but one that is particularly relevant to soil maps is the simplicity of the classification or legend. Ultimately, it is the understanding of the classification that will determine the legibility of the map.

Ensure users understand the concepts used for map production by referring to relevant chapters in these *Guidelines* and clearly explain that spatial units (e.g. soil–landscapes, land systems, unique mapping areas) should not be equated directly with taxonomic units (e.g. soil profile classes, taxa from the Australian Soil Classification).

Users of maps vary in their requirements, skills and expectations. Most are not versed in soil science and the complexities of survey method. However, they do expect the following (Thwaites 1999):

- accuracy and reliability of information at any scale
- information that is useable for different purposes and situations
- clarity
- an attractive presentation
- availability at a reasonable cost.

Interpreted maps

Interpreted maps (e.g. land suitability) require meaningful titles, explanation of the land utilisation type, and information on the attributes and critical limits used to derive the map. Include the original boundaries on interpreted maps for context. Each type of interpreted map requires a unique identifier, metadata and statements on fitness of use. Make sure the edition number and date of production are included.

Soil–landscape models

It is difficult to adequately represent patterns of soil and landscape variation on a map. Compromises are inevitable – this can be frustrating for surveyors because the richness of their insights cannot be fully represented.

Digital technologies still rely on maps for representing soil and landscape variation. However, interactive options, including links to text, images, audio and animations, are allowing far more effective ways of representing landscape patterns and processes.

Digital communication products

Another advantage of digital technologies is the smaller cost of publication. Conventional maps and reports are expensive and inflexible. Once printed, reports and maps are limited in supply and expensive to update. Digital products can overcome some of these problems.

Digital publishing continues to advance and the range of possibilities is increasing. A digital product may be as simple as a scanned copy of a traditional report or as complex as a specifically written computer application or web map or feature services (see *Chapter 25*). Although digital products can provide an effective and powerful means of communication, they can add another level of complexity to the publication process. Some of the issues involved in producing digital products for the communication of land resource information are considered here. Refer to Snooks (2002) and future revisions of this monograph for a definitive account.

Types of distribution media

Selection of appropriate distribution media is critical and it influences the form of the final product. At the time of writing, there are two clear options, the:

1. static medium of the Compact Disk (CD) or Digital Versatile Disk (DVD)
2. dynamic medium of the Internet.

These technologies are allowing large data sets to be distributed along with associated browsing software.

CDs have the advantage that they are inexpensive, easy to produce and have a relatively large storage capacity (about 650 Mb). DVDs are more expensive to produce but are emerging as a viable physical storage medium with a 10-fold increase in capacity. Once the information is compiled and the disk produced, it cannot simply be updated by the publisher. CDs or DVDs are therefore an ideal medium for distributing information that changes little over time.

CDs and DVDs can be easily copied and redistributed so copyright control may also be an issue. Many organisations have strict controls on intellectual property and the associated rights are often defined under restrictive licensing agreements. However, where the information is to be made freely available, the ready duplication of CDs and DVDs may have a positive impact that aids wider distribution of the products.

The Internet is an ideal medium for reaching a wide range of people whose whereabouts are neither known nor required. Text and images can be readily prepared using standard code (e.g. HTML or XML) and software. Before launching into Internet delivery, consider the following.

- Some sectors of the community do not use the Internet.
- Slow download speeds in remote locations means that any publishing on the web requires a careful analysis of user requirements. The Internet is more suited to the presentation of interpreted information and not large-volume raw data sets. The download speed available to the target audience needs to be kept in mind (many rural communities do not have high-speed communication lines). If the target audience is in a local office connected to a high-speed network, then this may not be an issue.
- Small organisations may have difficulty securing a reliable and long-term Internet Service Provider (ISP). Most large organisations have their own resources, but smaller organisations will need to use commercial providers. The costs can be a large component of the project budget. Other issues to consider include security, virus controls and version control.
- The Internet gives organisations the opportunity to create relatively dynamic information packages that can be kept current and relevant at low cost. It is an ideal medium for information that is constantly changing or evolving. Given this dynamic nature, the long-term maintenance of published web pages becomes important. Some products can become dated and irrelevant. Constant monitoring of content is necessary to produce a useful website.

- The Internet allows easy access to a wide audience. The audience generally cannot be specifically targeted, so the onus is on the publisher to produce information with a broad appeal and useability.

Types of products

Most agencies in Australia have moved away from paper reports and maps to digital formats. As computers have become more accessible and their capacity expanded, the types and quantity of electronic publications have multiplied dramatically. Interpreted products (e.g. maps of land suitability for various land uses) may range from existing hardcopy products, which have been scanned, to special-purpose computer programs. Digital products can be augmented with a broad range of multimedia components used to help explain complex concepts (e.g. pop-up graphics, text boxes, audio explanations, interactive animation). The digital environment gives the publisher the flexibility to include components that will most closely suit the client's needs.

Document formats

Digital documents can be published in a broad range of formats.

Proprietary word processing

Typically, land resource reports are generated as a word-processed document and then sent to publishers who produce hard copies; alternatively, they may be distributed by some electronic means. In some cases they may be produced as in-house publications using colour printers and manual binding. The main problem with word-processed documents is that the user may need to have the same software available to them as did the generator of the document. These documents are also insecure and become susceptible to alteration and corruption. Documents generated with word-processing packages are generally not published directly on the Internet but can easily be distributed via CD or email.

Portable Document Format (PDF)

Adobe's Portable Document Format (PDF) is the *de facto* standard for electronic document distribution. It is a universal (although proprietary) file format that preserves fonts, formatting, graphics, and colour of any source document, regardless of the application and platform used to create it. The files are compact and can be shared, viewed, navigated and printed exactly as intended (more or less) by anyone with freely available software. However, purchased software is needed to create the files. The format is good for reports and traditional style maps in an electronic form.

The typically small file size of PDF documents makes them well suited to web publishing. A document can be read directly by the web browser or downloaded from the Internet and opened in the reader software. The size of files can be adjusted according to the means by which they will be disseminated (i.e. file sizes can be 'distilled' to a smaller size for faster loading on the Internet).

An excellent example of this style of publishing is the Regional Land Information Series produced by the South Australian Department of Land, Water and Biodiversity (SADWLBC 2006). This set of CDs contains maps and land resource information for South Australia's agricultural districts. Information is presented in the form of PDF documents (Figure 32.4, Plates 4 and 5, pp. 422–423) containing:

- maps of land systems and soil landscapes
- descriptions of each land system and soil landscape (including soil site sheets)
- photographs, descriptions and data for representative soils

- regional maps depicting a range of attributes that influence agricultural land use
- the assessment criteria used to produce the attribute maps.

Web pages

Websites link text and graphics files via hyperlinks – they enable vast amounts of information to be easily organised and accessed. Websites are diverse and rapidly changing as a short exploration with standard search engines will demonstrate. The ASRIS (2006) and VRO (2006) websites are good starting points for information on land resource assessment.

The VRO (2006) website has a wide range of natural resource information (e.g. climate, landform, soils, vegetation, land and water management). Land resource survey reports are available as downloadable PDF-format documents. In addition, several soil and landform maps are provided as interactive web pages. Users can click onto maps to reveal descriptions of map units and information on soil profiles (with links to glossary entries).

Images

The main issues to consider when using images relate to size and quality. An image of a map needs to be of excellent quality in a digital environment if it is to portray as much detail as a printed map. High quality images require large file sizes, and this can create problems due to slow transfer. The cost of placing colour graphics on the Internet is smaller than that associated with printing and distributing traditional maps. This alone may make the use of digital-based images more appealing to some suppliers of land resource information. The use of interactive Internet-based mapping is discussed in the next section.

Multimedia

Land resource information can be very technical and difficult to understand. The use of multimedia (i.e. computer-based text, audio, image and animation) can improve the communication process but development costs are usually large. The use of video can add significant information content to a web page. Video files can range from simple animations to full-quality movies with sound (multimedia cartography). Good examples of its use in land resource information products include animations to demonstrate landscape processes and 3D fly-throughs of landscapes with associated land resource information.

Simple web pages provide a good deal of flexibility to publishers but, once generated, are static. The user cannot interact with web documents other than through hyperlinks. Creative use of a range of web technologies (such as CGI scripts, Java, JavaScript, DHTML and ActiveX controls) have made it possible to create more interesting and effective web sites. However, large file sizes and bandwidth issues can make these applications prohibitive for some.

Online Geographical Information Systems

The advent of interactive GIS via the Internet is a fundamental advance for land resource assessment. Maps presented on the Internet as static images only convey similar levels of information as do traditional paper maps. Interactive GIS allows the user to acquire custom-made maps. One type of dynamic interaction is the use of CGI scripting to provide interactive access to databases and spatial data sets. A more useful interactive method allows the user to determine the areas of interest, and data layers depicted, through use of online systems for mapping.

Providing access to live data in a dynamic fashion via web-based databases and GIS has many advantages, including providing a high level of functionality at relatively low cost. These types of systems tend to be more expensive to set up but, once running, provide users with the power to query and analyse data as the need arises. Examples include the NLWRA (2006), NSW Department of Natural Resources (2006), ASRIS (2006), Google (2006) and NASA (2006).

The NSW Soil and Land Information System (SALIS) includes descriptions of soils, landscapes and other geographical features from across the state. SALIS has been developed as a centralised repository. Duplication of effort is eliminated by storing soil and land information in a single system. Information can be stored in SALIS on a confidential (access only to the owner and system administrator) or public (available freely to all) basis. One means of accessing SALIS soil profile information is online using the Soil Profile Attribute Data Environment (SPADE) (NSW Department of Natural Resources 2006) (Figure 32.5, Plate 6, p. 424).

Customised computer programs

Purpose-written computer programs are another means of distributing land resource information. These types of products tend to have a well-defined target group and often provide many functions. Examples include the Interactive Key to the Australian Soil Classification (Jacquier et al. 2001) and the Oz Soils educational tool for soil science (Lockwood and Daniel 2002). Bowler (2002) provides an excellent Earth-science example.

Data presentation and visualisation

There are many options for graphical presentation of survey data. Good graphical displays should:

- show the data
- induce the viewer to think about the substance rather than the methodology or graphic design
- avoid distorting what the data have to say
- present many numbers in a small space
- make large data sets coherent
- encourage the eye to compare different data
- reveal the data at several levels of detail (from broad overview to fine structure)
- serve a clear purpose (e.g. description, exploration or decoration)
- be closely integrated with statistical and verbal descriptions of the data set (Tupte 2001).

Some methods can be used for more effective communication (see *Chapter 21*), especially when the target audience is technically minded. Remember to use colour wherever possible. Such graphics are more appealing, can convey more information and are readily recalled. The Victorian Resources Online web site has a section on geographic visualisation, including links to relevant web sites (Figure 32.6, Plate 7, p. 425).

Communication activities

Field days based on soil pits

A soil pit can be used as a talking point and focus for communication during, or at the end of, a survey. They are valuable for training and education, especially for:

- introducing major soil types, their variants, and methods for recognition (e.g. diagnostic horizons)
- revealing soil variation
- showing key morphological features (e.g. mottle patterns, structure, slickensides, impeding layers)
- demonstrating relationships between soil characteristics and management (e.g. dispersion tests)
- relating soils to broader landscape features.



Figure 32.7 Soil-pit field day held for a Landcare Group. Companion booklets containing soil and landscape information were provided as part of the field day.

Field days centred on soil pits are a useful complement to the large literature devoted to improving land literacy (Figure 32.7). Aids to land literacy assist landholders read the land and detect early signs of degradation or poor performance. This places them in a position of being able to do something about the problem (PDP 1993). These aids use plenty of illustrations and are written in plain English. An example is the Soil Structure Assessment Kit (McGuinness 1992).

Have a range of experts at soil-pit field days (e.g. pedologist, agronomist, hydrologist, forester). Attendees are often seeking agronomic interpretations and these should be linked as much as possible to soil profile morphology and characteristics.

Soil characterisation and classification workshops

Soil pits are used by various agencies as a focal point for soil characterisation and classification workshops. In Victoria, these have been designed to increase awareness and understanding of soil characterisation and classification among regional staff who have an interest in soil and land assessment and management. Take-home notes are prepared and used during the workshop. These contain copies of overheads and a soil classification exercise sheet. The morning session provides a brief overview of soil characterisation as well as previous soil classification schemes and the Australian Soil Classification and its Soil Orders. An exercise in classifying a soil profile is then completed indoors. The afternoon session focuses on several soil pits nearby (usually representing a few Soil Orders). These are characterised and classified in the field, reinforcing the indoor sessions.

SOILpak

SOILpak is a manual with an associated extension program aimed originally at improving soil management in the cotton industry. Daniels et al. (1996) outline its history. SOILpak gathered

information from researchers, agronomists and leading growers in a format that was easy to follow. Associated field days involving soil pits provided opportunities to discuss soil management in relation to landscapes and diagnostic soil properties. The latter were characterised with simple tests for dispersion, plastic limit and other factors affecting root growth and water movement (McKenzie 1998).

Assessment of yield trends and a survey of SOILpak clients indicated that the manual had assisted in improving farming practices. By helping growers with soil management, the manual accelerated the industry's trend towards adopting minimum tillage, permanent beds and controlled traffic. It provided good options for growers and their advisors based on the results of a semi-objective assessment of soil structure. The major features of the SOILpak manuals included:

- links to associated information in other chapters
- effective use of diagrams, tables and flow charts for making decisions
- glossary of terms
- soil description sheets with completed examples
- a summary booklet for field use.

SOILpak has been disseminated widely in Australia. A 20-minute instructional video has also been produced. It shows how to use the manual along with testimonials from key landholders and consultants – a valuable source of credibility for the project. The soil management training packages produced by Larsen (1994) include posters to use at field days, a pocket version of SOILpak for experienced users, and sets of stereo pairs. The stereo pairs capture, with colour slides, a wide range of soil structures (Daniels et al. 1996).

Promotion and marketing

Radio, television and print media provide ways to reach broader audiences. The best option is to work with a journalist as the intermediary for getting your message across to the target audience. The message should be simple. Do not assume the journalist has prior knowledge. In particular:

- find a point of interest or importance to which the average reader or listener can relate (the hook)
- find a novel approach that will keep the average reader interested (the angle)
- use appropriate metaphors and analogies
- provide written material for the journalist together with your contact details
- avoid technical jargon and clearly explain unavoidable terminology.

Although declining in importance, the print media still reaches a large audience and is worth pursuing. Various newspapers will cover different regions, from local to state-wide. The message is more likely to appeal to a newspaper editor if it appeals to all readers (e.g. not only farmers), has some element of human interest (e.g. the salinity problem has had a significant effect on a farmer's livelihood), can be illustrated with an image, or has local relevance.

Manuals, brochures and fact sheets need to be clearly written and show good graphic design. Robinson (1989) notes the following:

- people will feel good about using your publication if it is relevant to their needs and they can quickly find what they need to know
- break long sections into small modules, preferably with illustrations and graphic signposts, to help readers find what they need quickly
- simplify and aim for brevity

- build your writing on the reader's knowledge, not your own
- create visual interest with good graphic design, which makes publications more interesting and accessible; thus, capture and maintain the reader's attention, create visual signposts, and lead the reader through the publication according to the natural direction of reading.

Include informative captions with your images. Also place key points in captions so that individuals scanning the document have their interest captured and are encouraged to read further.

Conclusions

- Understand the information needs of your audience.
- Prepare a formal communication plan addressing the needs of relevant audiences.
- Engender ownership of the survey across a wide range of stakeholders.
- Provide progressive reporting to stakeholders using concise and preferably visual formats.
- Prepare products that are accessible and use visualisation to convey findings and results.
- Choose appropriate media to disseminate survey information.

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