MANAGING FOREST ECOSYSTEMS

Computer Applications in Sustainable Forest Management

Including Perspectives on Collaboration and Integration

Edited by
Guofan Shao and Keith M. Reynolds

Springer

COMPUTER APPLICATIONS IN SUSTAINABLE FOREST MANAGEMENT

Managing Forest Ecosystems

Volume 11

Aims & Scope:

Well-managed forests and woodlands are a renewable resource, producing essential raw material with minimum waste and energy use. Rich in habitat and species diversity, forests may contribute to increased ecosystem stability. They can absorb the effects of unwanted deposition and other disturbances and protect neighbouring ecosystems by maintaining stable nutrient and energy cycles and by preventing soil degradation and erosion. They provide much-needed recreation and their continued existence contributes to stabilizing rural communities.

Forests are managed for timber production and species, habitat and process conservation. A subtle shift from *multiple-use management* to *ecosystems management* is being observed and the new ecological perspective of *multi-functional forest management* is based on the principles of ecosystem diversity, stability and elasticity, and the dynamic equilibrium of primary and secondary production.

Making full use of new technology is one of the challenges facing forest management today. Resource information must be obtained with a limited budget. This requires better timing of resource assessment activities and improved use of multiple data sources. Sound ecosystems management, like any other management activity, relies on effective forecasting and operational control.

The aim of the book series ***Managing Forest Ecosystems*** is to present state-of-the-art research results relating to the practice of forest management. Contributions are solicited from prominent authors. Each reference book, monograph or proceedings volume will be focused to deal with a specific context. Typical issues of the series are: resource assessment techniques, evaluating sustainability for even-aged and uneven-aged forests, multi-objective management, predicting forest development, optimizing forest management, biodiversity management and monitoring, risk assessment and economic analysis.

The titles published in this series are listed at the end of this volume.

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Dedication

This book is dedicated to digital foresters in the information era

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Preface

Earth, and the often far-reaching impacts of its human inhabitants, can now be viewed and represented with digital information ranging from satellite imagery to geospatial databases. Increasingly, scientists, policymakers, and the general public have come to appreciate the need to better understand our planet and how we are affecting it. Among the array of impacts that have attracted global attention, those to forests figure prominently. Impacts to forest ecosystems are of special concern because, while forests provide goods and services essential to the well-being of human societies, and indeed to the proper functioning of global systems, they are disappearing faster today than ever before.

At the same time as we have been witness to unprecedented changes to forest ecosystems, there has also been a rapid evolution in information management and information technologies, and it has been proceeding at an almost breath-taking pace. Many of these digital technologies have become integral to modern forestry operations in many countries. Efficiencies have been achieved in such areas as pre-harvest quality assessment, production planning, resource assessment, systems analysis, management, field operations, environmental impact, and day-to-day decision-making. In short, forestry technologies have become, and are continuing to become, increasingly digital.

Recognizing the degree to which many core forestry operations had indeed become increasingly digital in the above sense, the Society of American Foresters (SAF) and the Chinese Academy of Sciences jointly sponsored the 1st International Workshop on digital forestry, which was held in Beijing between June 13 and 19, 2004. The workshop provided a venue in which scientists, representing a broad array of digital disciplines in forestry, could discuss the convergent development of digital forestry as a new integrative discipline, grounded in the state-of-the-art applications of digital disciplines in forestry, including forest inventory, remote sensing, geographic information systems (GIS), forest modeling, biometrics, and decision science. Overall, 30 participants from China, the United States, the United Kingdom, Germany, and Canada attended the workshop.

The participants in the 1st International Workshop on digital forestry have made a concerted effort to summarize the state-of-the-art of computer applications in major disciplines, and offer insights on how they relate to each other with a view toward their collaborative application. Additional forest scientists, who could not attend the workshop, also were invited to participate in this effort in order to fill important gaps in subject matter that were identified in follow-up discussions after the initial workshop. This book volume represents the outcome of the overall discussion during and after the workshop.

Acknowledgments

We would like to thank Dr. Guang Zhao, past Chair of GIS Working Group of SAF, for his many efforts in initiating and facilitating the workshop, Dr. John Moser, reputable forest biometrician and past President of SAF, for his enthusiastic advising on the workshop, and Dr. Tang Shouzheng, Academician of Chinese Academy of Sciences, for his courage in proposing the workshop. We also thank the workshop supporters: the Chinese Academy of Sciences, the Chinese Academy of Forestry, Jilin Yanbian Forestry Group, and China's Natural Science Foundation. There were a number of important participants, including Mr. Brett Martin and Drs. James Brey, Andreas Huth, Steen Magnussen, John Moser, Keith Rennolls, Yunjun Sun, Ronghua Ye, Lianjun Zhang, and Guang Zhao, who made significant contributions to the workshop discussion, although they did not write chapters for this volume.

The staff at Springer has been extremely helpful in providing assistance with the preparation of this volume. Reviewers of the book proposal made many constructive suggestions, which helped to shape the ultimate contents of the book. All the contributors spent much time and resources in preparing individual chapters. Special thanks are extended to a cadre of patient and valuable reviewers: Drs. Thomas Barrett, David Darr, Jeremy Fried, Han Sup Han, John Kushla, Don Leckie, Alan Murray, Andreas Reinbolz, Brad Seely, Stephen Shifley, Kenneth Skog, Alan Thomson, Xianli Wang, Jingxin Wang, and John Weishampel.

Finally, special recognition is due to the senior editor's wife, Junhua, son, John, and daughter, Jenny, who scarified quality family time, but provided him with much free time for preparing this book.

As editors, we welcome comments and suggestions on anything in the book.

Guofan Shao
Keith M. Reynolds

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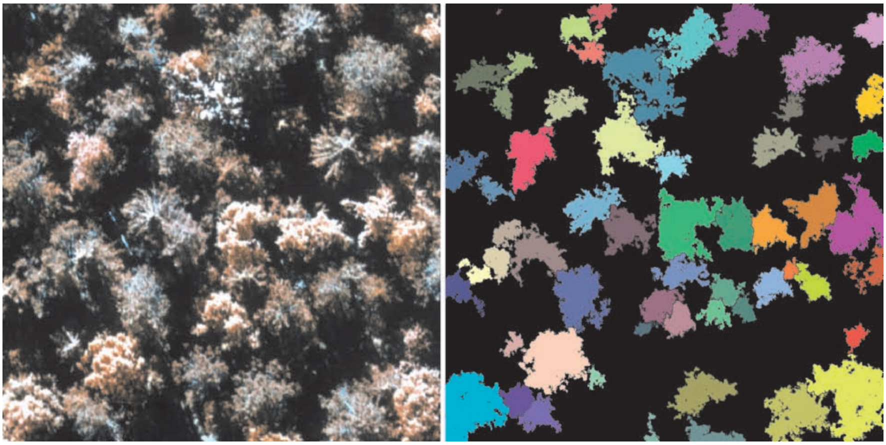

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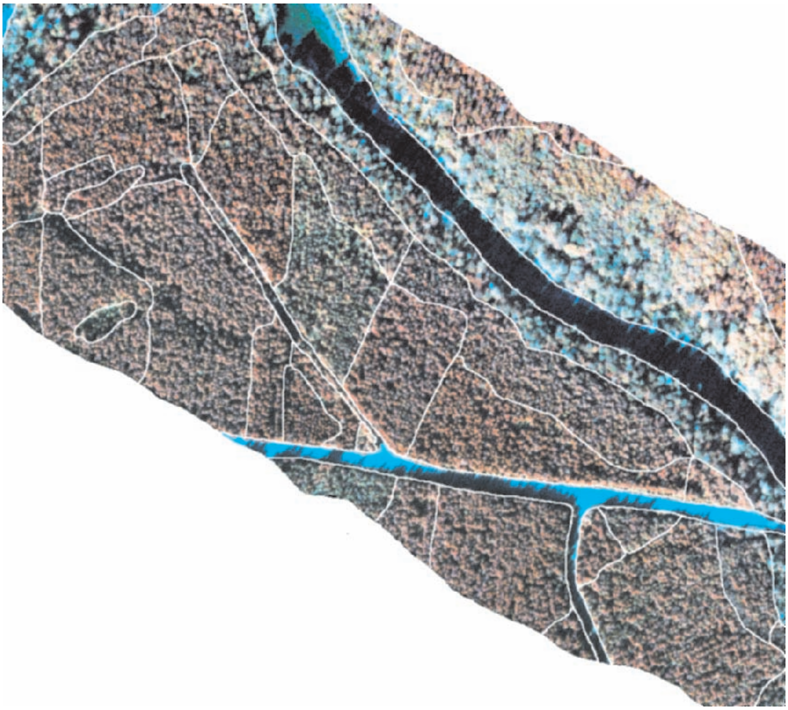

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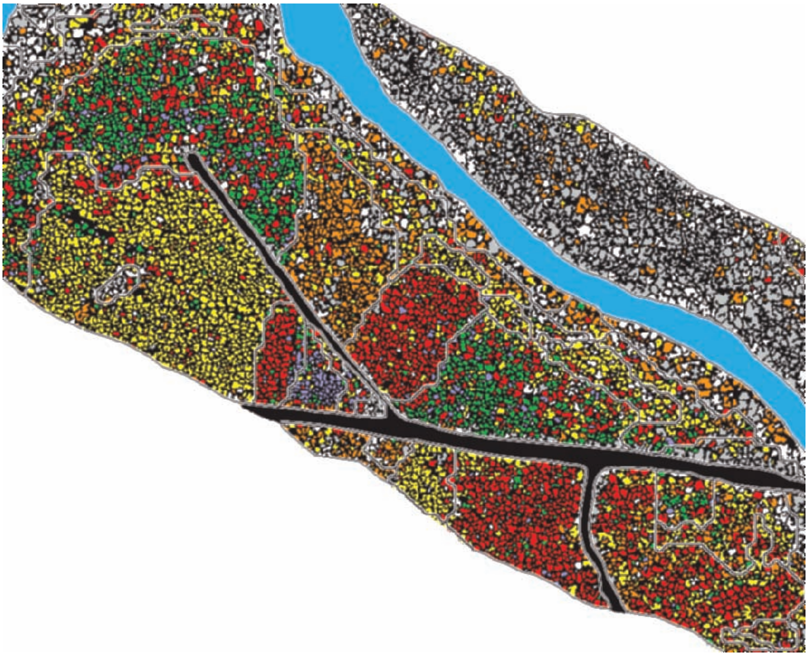

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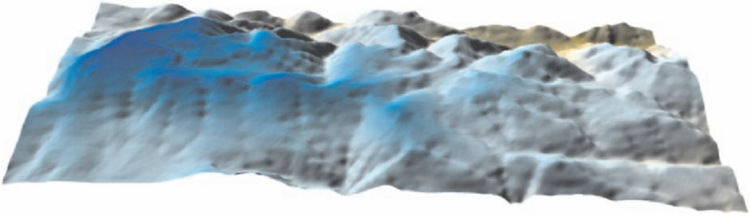

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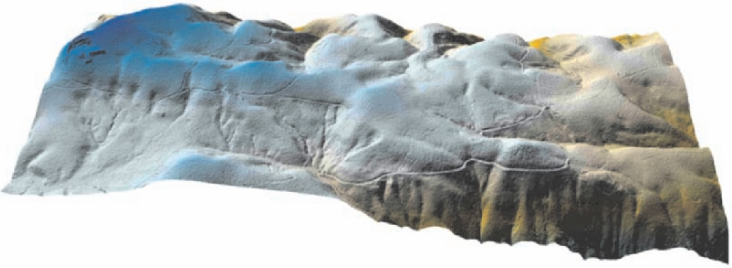

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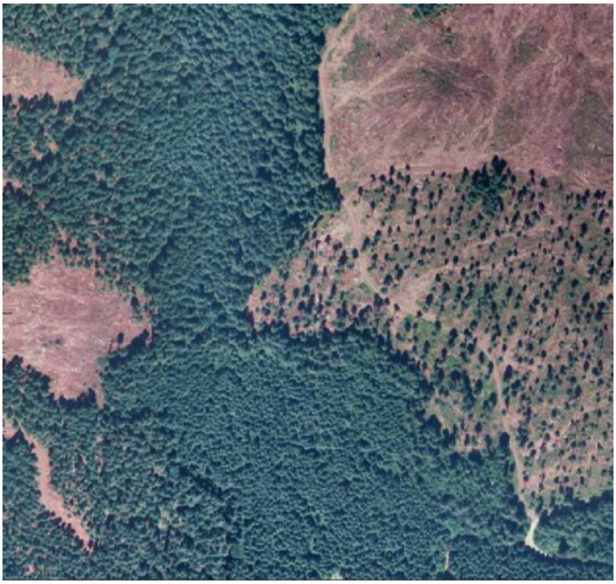

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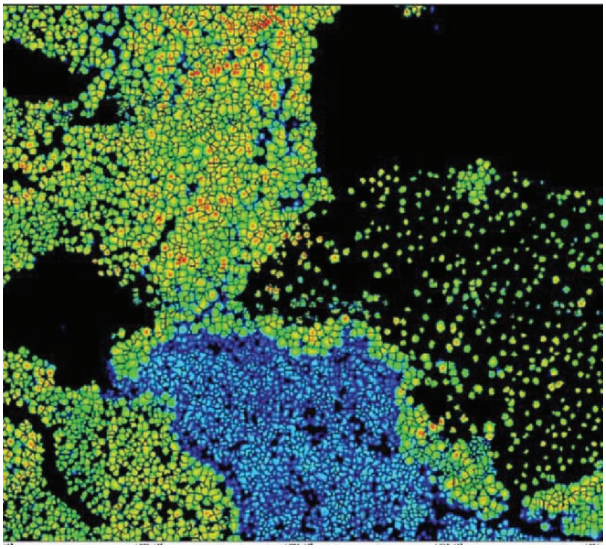

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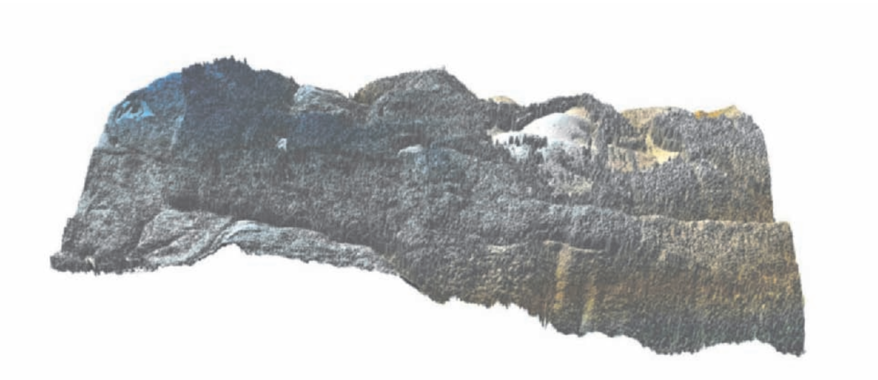

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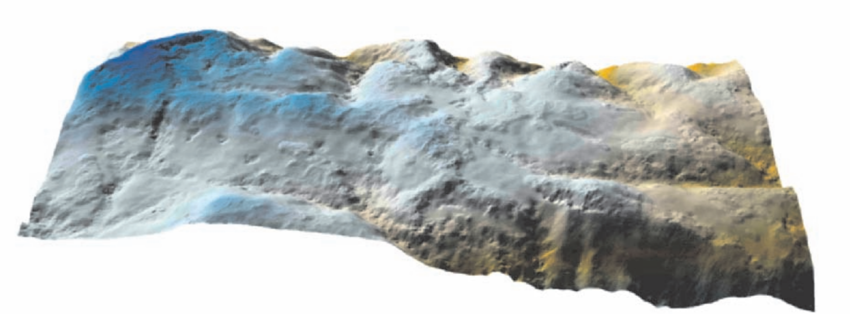

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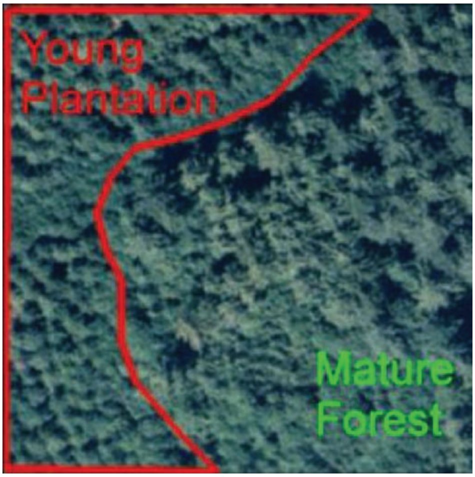

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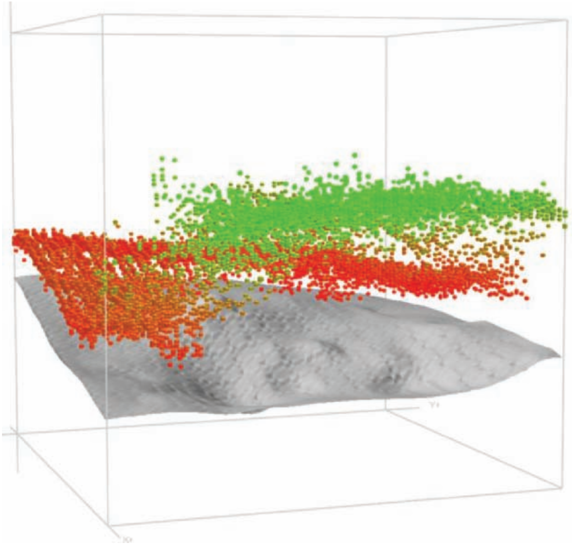

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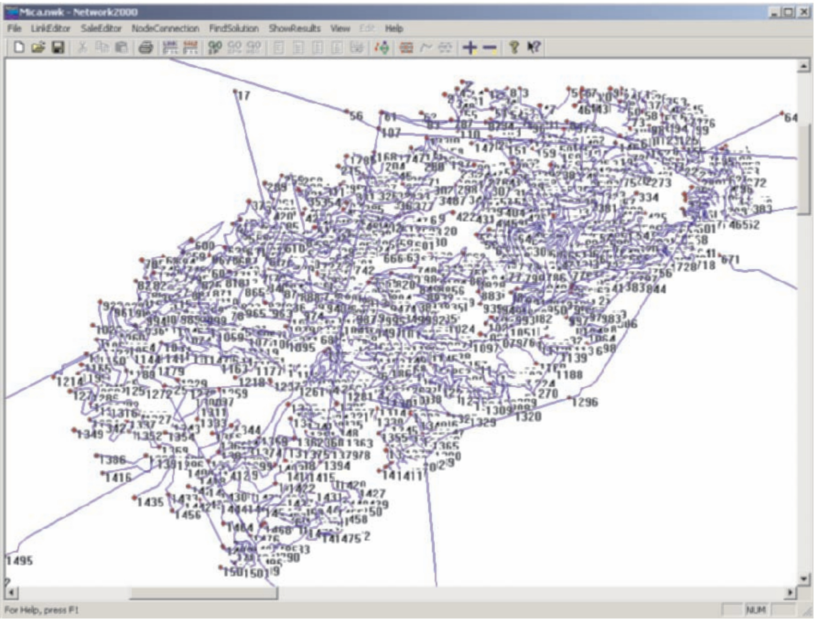

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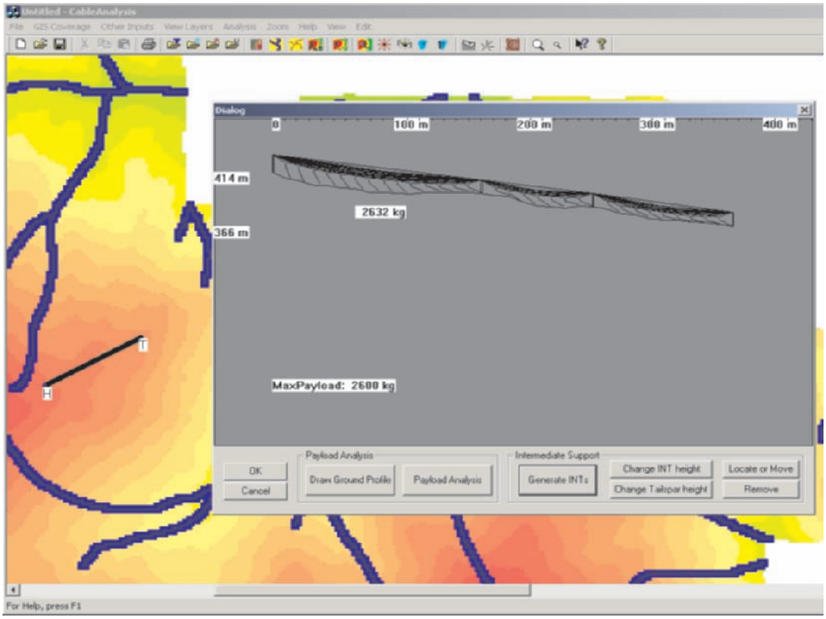

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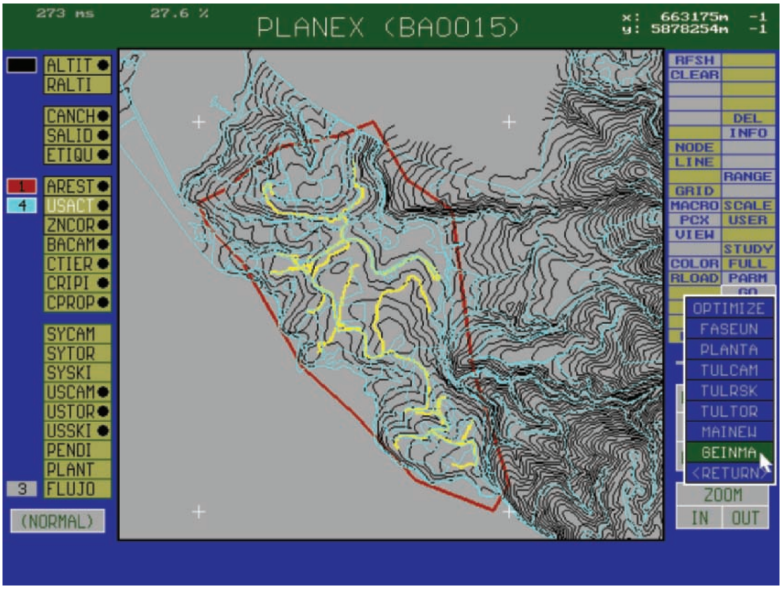

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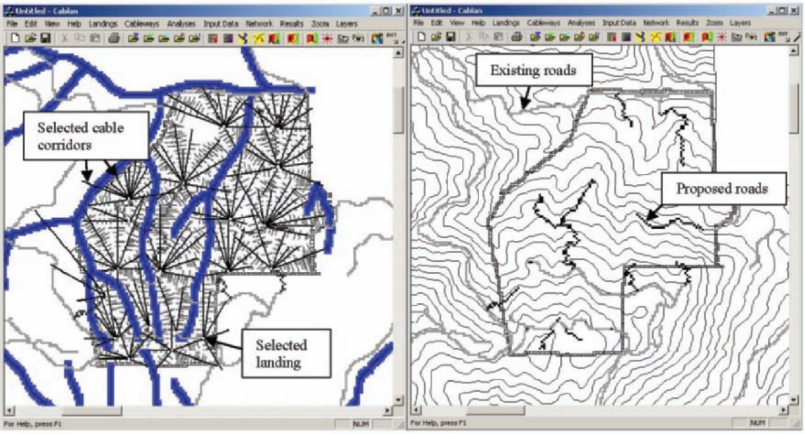

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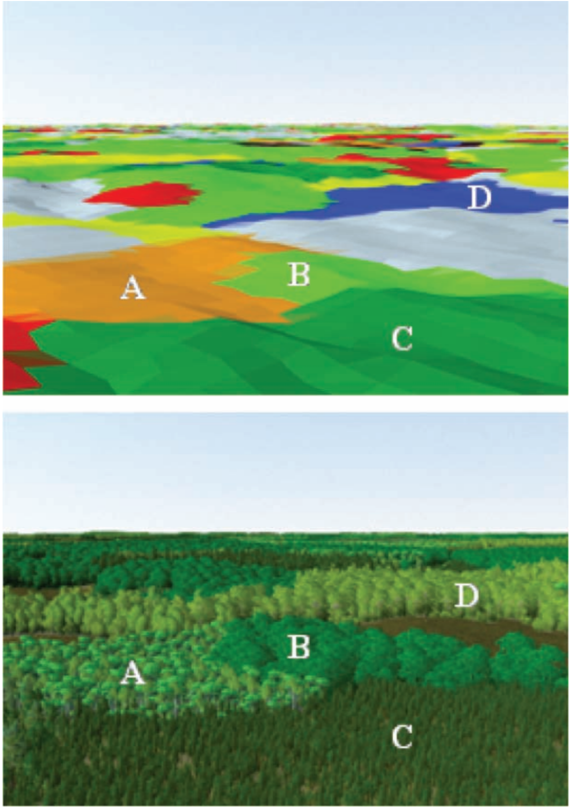

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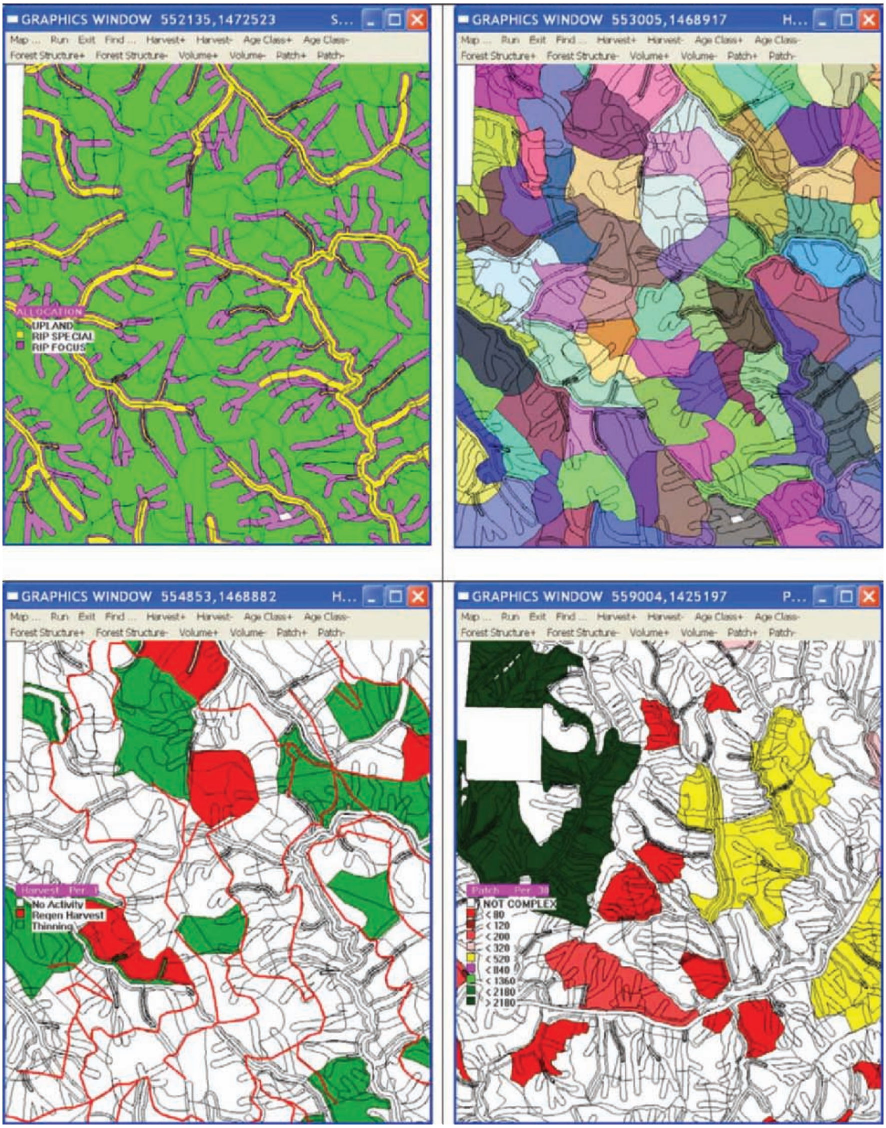

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PART I

INTRODUCTION

.

Chapter 1

INTRODUCTION*

Digital forestry

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Abstract: This chapter introduces the concept of digital forestry, and explains how it has provided the motivation for this volume. We also provide a brief overview of some major disciplinary areas as a prelude to more in-depth discussions of subsequent chapters, introduce the remaining chapters of this volume, and describe the goals and objectives of this work.

Key words: Digital forestry; sustainable forest management; remote sensing; geographic information systems; visualization; decision support systems.

1. WHAT IS DIGITAL FORESTRY?

Digital forestry is *the science, technology, and art of systematically acquiring, integrating, analyzing and applying digital information to support sustainable forests* (Zhao et al. 2005). Although many forest scientists and forestry professionals are already applying a wide variety of digital technologies in forestry, the gap between contemporary forestry and the concepts embodied in digital forestry is significant. Digital forestry can function as bridge that links the producers and users of digital technologies in forestry (Figure 1-1). In particular, in recognizing the need for a new discipline designed to support sustainable forestry, participants were, in effect, acknowledging the importance of a very broad educational experience in the whole array of disciplines that might be brought to bear to better support sustainable forestry. We doubt that any of the participants envisioned that a student of digital forestry (a digital forester, if you will) would be expected to master all the relevant digital technologies. Rather, by

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having a broad, working understanding of all the relevant disciplines, a specialist within any particular discipline would be far better equipped to collaborate more effectively with their colleagues. The latter idea is, in fact, the key motivation behind *Computer Applications in Sustainable Forestry*.

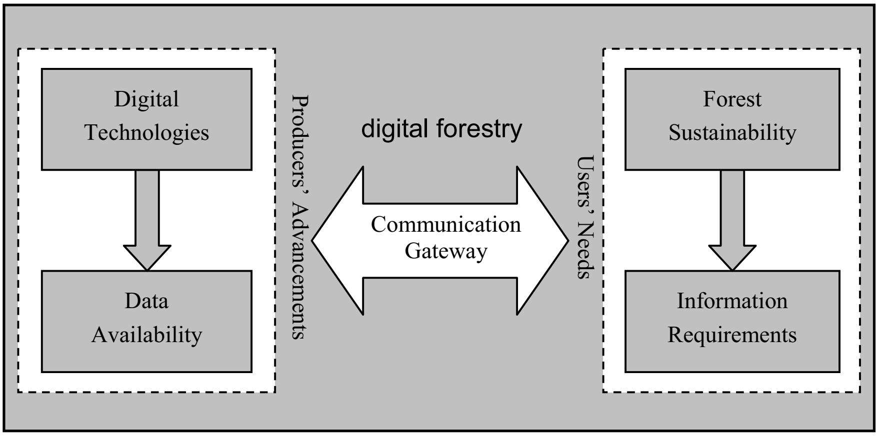

Figure 1-1. An illustration of the roles of digital forestry in bridging the producers and users of digital technologies in forestry.

2. CONTEMPORARY COMPUTER APPLICATIONS IN FORESTRY

2.1 Remote sensing

Compared to ground survey of forest resources, remote sensing technology has some obvious advantages. For example, remote sensing provides rapid coverage of large areas, permanent and objective records, map-like products, efficiency in time and money, and access to inaccessible areas. In the United States, the techniques of aerial survey for forestry were developed in parallel with the increasing availability of vertical aerial photographs in 1940s. As Sisam (1947) points out, interest in aerial photography stems from its obvious advantages: increasing mapping accuracy, expanding spatial coverage, providing stereo-vision, reducing total time in mapping, providing permanent records, covering inaccessible areas, and recording changes over wide areas. The Cold War arms race between the United States and Soviet Union stimulated the rapid technological advancement of satellite-based remote sensing capabilities for military applications. Civilian applications of spaceborne remote sensing did not start until the 1960s. There were only 3 civil remote sensing satellites in the 1960s and 4 in the 1970s, but the number jumped to 8 in the 1980s and 16 in the 1990s (SCSAC 2000). Since the 1970s, digital remote sensing has renewed and expanded capabilities for data acquisition that are improved with the increases of spatial, spectral, temporal, and radiometric resolutions (Figure 1-2). Active remote sensing, such as RADAR and lidar, provide new means of data acquisition. All these advancements have significant implications to forestry.

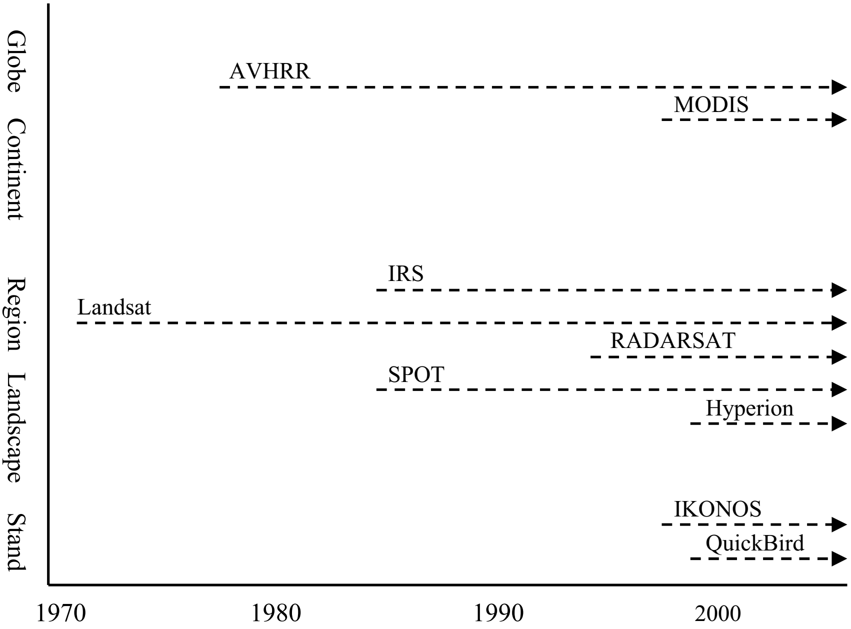

Figure 1-2. A brief timeline and spatial scale of major satellite remote sensors useful for the collection of forest resource information.

Holmgren and Thuresson (1998) summarized 25 years of experience in applications of remote sensing in forestry, and concluded that information derived from satellite images was insufficient to support the decision process in applied forestry. However, Wulder (1998) believed that new analysis techniques and advances in remote sensors would help obtain detailed measurements useful for sustainable forestry. Since 2000, several academic journals have published special issues or sections on the application of remote sensing in forestry. The special issue in the Journal of Forestry in 2000 focused on the role of remote sensing in forestry and the relationship between forester and remote sensing specialist (Bergen et al. 2000); the special issue in Forest Science in 2003 collected articles covering a reasonably representative cross-section of the scope of remote sensing applications in forestry (Wynne 2003); the special section in BioScience in 2004 dealt with advanced applications of remote sensing in ecology (Cohen 2004).

Remote sensing may be the only practical way to provide sustainable forest management with required data, such as synoptic and repetitive biophysical and biochemical vegetation data for large geographic areas over long periods of time (Franklin 2001). Remote sensing in forest resource assessment provides at least three levels of information: the spatial extent of forest cover, the forest type, and the biophysical and biochemical properties of forests (Boyd and Danson 2005). However, to apply remote sensing in production forestry, the needs of sustainable forest management and the capabilities of remote sensing will need to be reconciled (Smith et al. 2003). The combination of new technologies for remote sensing and new techniques for data analysis are likely to narrow the gap between users' needs and producers' products.

Recent advances of remote sensing technology in forestry are introduced in Chapters 2 and 3 of this volume.

2.2 Geographic information systems

One of the most significant technological developments for forest and natural resource organizations during the past century has been the advent of geographic information systems (GIS) (Wing and Bettingfer 2003). There are many different definitions of GIS (Clarke 2001), but the basic concept, common to all definitions, is that GIS is a computer-based technology that is used to solve problems, perform queries, and derive answers or solutions by digitally manipulating *spatial* data.

Many applications of GIS in forestry began appearing in the 1980s. In the United States, early applications of GIS in forestry were initially developed in both federal and industrial forestry organizations (Smart and Rowland 1986, Consoletti 1986). They quickly proved useful as operational tools for forest inventory and planning. Although the primary products of the early forestry GIS were maps, they had clear advantages over the traditional techniques, such as light tables for tracing maps and planimeters for calculating areas. Even the early GIS technology had the ability to recall a map to apply changes to previously recorded information. This allowed foresters to update forest information in a timely manner when forest management activities, such as harvesting and planting, occurred.

During the past two decades, GIS technology has advanced in parallel with other computational technologies. As global forest resources continue to decline and human populations continue to grow (PAI 1999), sustainable management of forests has become increasingly more sophisticated and is being implemented with new considerations (Floyd 2002, Wang 2004), such as ecosystem management and adaptive forest management (Leskinen 2003, Thomas 1992). These new considerations in forestry need support from new data, new variables, and new methods for data analysis with a spatial context. Not surprisingly, GIS has become a useful tool for forest ecosystem management, fire management and control, silvicultural activities, forest access and road planning, and pest management (Berger and Rey 2004, Dean 1997, Hall et al. 1998, Pernar and Storga 2005). Although many applications of GIS in forestry have been designed with broad spatial scales in mind, Pernar and Storga (2005) also have pointed out that GIS can support management planning for areas as small as 1 ha, helping determine operations (silvicultural treatments, replanting, felling and others) in each plot separately. Furthermore, dealing with problems using a GIS technology releases forestry experts from routine jobs (manual mapping, constructing new layers from the existing ones and similar), leaving them with more time for decision making in spatial management and planning.

GIS is rapidly becoming one of the most useful and widespread tools in forestry (Bernard and Prisley 2005, Hetemäki and Nilsson 2005). Current GIS systems offer a variety of solutions, ranging from desktop software capable of carrying out daily work for individual forestry professionals to high-end systems capable of managing large spatial databases for large organizations. For example, ArcGIS (www.esri.com) is a popular GIS system with the ability to manage and manipulate spatial resource data in an amazing variety of ways. On the other hand, there are other GIS systems, available at low or even no cost, that are readily available on the Internet, and these may be sufficient for many potential applications in forestry (Varekamp et al. 1996). Bernard and Prisley (2005) reviewed some of these "small-scale" GIS systems in terms of platform and cost, ability to create new data, and system functionality, and concluded that even these much more modest systems can provide forest managers with useful options that may be adequate for their needs for management and analysis of spatial data.

GIS is a topic in every chapter of this volume.

2.3 Modeling and simulation

Forests have relatively long life spans, their structure and composition vary across space, and the myriads of components that make up a forest ecosystem are changing continuously over time. As a result, understanding how a forest changes within a period of time is far from trivial, but it is critically important in planning for sustainable forest management. Simulation modeling has proven to be a practical and effective approach for investigating forest dynamics across time and space, and can be an economically efficient way (it may, in fact, be the only way) to investigate the implications of different management strategies for processes such as growth and succession (Buongiorno and Gilless 2003, Shao et al. 1995).

Traditional forest modeling was mainly based on single-variable models, and used simple tables or diagrams to demonstrate processes of forest dynamics through time. The forest-yield table is a typical example. The historical development of forest-yield models occurred in two stages: normalized forest-yield models were the norm from 1787 until 1937, but density-dependent forest-yield models predominated between 1937 and 1960 (Moser 1980).

In the 1960s, the advent of computers made it possible to incorporate complex mathematic equations into forest-yield models, develop distance-dependent individual-tree models (e.g., Newnham 1964), and develop diameter-transition models (e.g., Usher 1966), and these new capabilities were primarily possible due to the relatively new tool of computer simulation (that is, computer-based process modeling). In the 1970s, new concepts in systems ecology caught the attention of forest-process modelers (Karplus 1977), and new types of simulation models, such as gap models (Botkin et al. 1972, Horn 1975, Shugart and West 1977), were developed for ecological analysis. Subsequently, simulation modeling began advancing along two parallel lines: forestry and ecology. In the past two decades, the relatively new concepts of ecosystem management have provided new challenges to forest managers, and, at the same time, simulation models from both forestry and ecology began to converge (Swanson and Franklin 1992). In the process, applications of simulation have expanded from stand, to landscape, to region, and even broader spatial scales by linking forest models with GIS and remote sensing data (Peng 2000, Porte et al. 2002).

A variety of forest models are described in Chapter 6. Modeling approach is also introduced in other chapters.

2.4 Visualization

Visualization is one of the most rapidly advancing of all contemporary computer technologies for forest management. Visualization techniques can be used to display trees, stands, and forested landscapes in virtual environments of 2D or 3D static graphics as well as in 2D, 3D, or 4D animations. Forest visualization can help forest managers better understand habitat disturbance, visual impacts, operational considerations, and overall or specific design features of forest management activities (PFC 2005). Forest visualization is also helpful to enhance the display of geospatial data and interpretations of forest simulations (Burkhart 1992, Tang and Bishop 2002, Thuresson et al. 1996). Thus, forest visualization has been proving useful for a broad range of specific forest management activities, such as ecosystem management (Daniel 2001), pest outbreaks and management (Lynch and Twery 1992), silvicultural treatments (Stoltman et al. 2004), and clear-cutting (Tonnes et al. 2004).

Techniques involved in environmental visualization range from simple visual images (photographs) to mathematical images (formulae) at local, regional and global scales (Larson 1992). Karjalainen and Tyrvainen (2002) have suggested that working on mathematical images is less labor-intensive than editing visual images and is not restricted to representation of limited areas in the manner of photographs. More realistic visualizations can be achieved by using more advanced structural data from LIDAR (Kao et al. 2005), and by using real-time graphic techniques (Wesslen and Seipel 2005).

Visualization is covered by at least three chapters in volume.

2.5 Decision making

In many ways, the essential elements of modern decision science originated with concepts from organization science, first elaborated by Simon (1960). Indeed, central concepts that emerged from organization science, such as bounded rationality as a pragmatic approach to solving problems, are still very much with us today. Mintzberg et al. (1976) proposed a very general model for rational decision-making processes in which individuals or groups are guided through a series of tasks from problem identification and analysis to design of alternatives and selection of an alternative (Figure 1-3). This model has stood the test of time. Virtually all approaches that implement a rational approach to decision making can be understood as variants of the basic Mintzberg model.

Within the scope of this volume, we consider an array of approaches to decision making that have been contributed from such diverse disciplines as operations research, statistics, management science, and artificial intelligence.

In recent years, however, a variety of new approaches to decision making have been proposed and tested as ways of overcoming some of the perceived limitations of a strictly rational model. Some of the new techniques include collaborative learning (Daniels and Walker 1996), the dialectic approach (Elgarah et al. 2002), and consensus building (Vincke 1992). Although some authors have tended to cast these new approaches as alternatives to rational models, it is perhaps more constructive to think of them as enhancements to the rational model (Ekbia and Reynolds 2006).

These new approaches are not addressed further in this volume, but we encourage readers to explore the concepts, and consider how they might be incorporated into the application of decision-making tools discussed in Chapter 8.

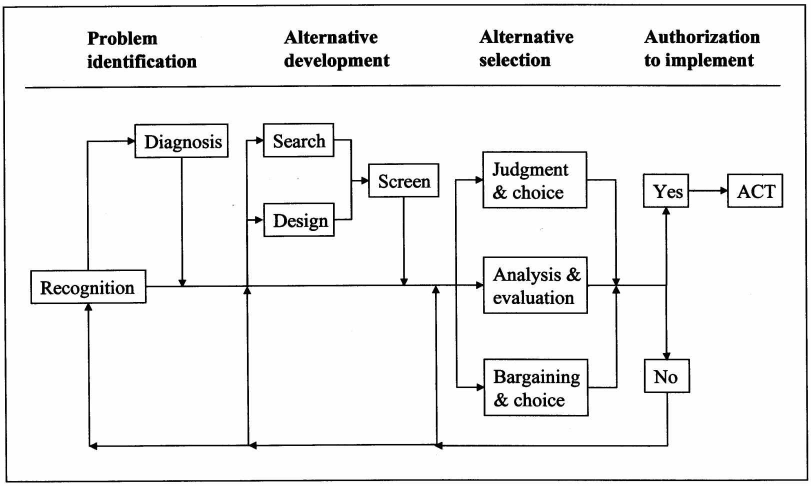

Figure 1-3. The Mintzberg model (Mintzberg et al., 1976), after Rauscher (1999). The Mintzberg model presents a general approach to decision making, representing all, or at least most of, the classic variations on a typical planning process. The process proceeds through the four steps of problem identification, alternative development, alternative selection, and a final decision to either implement the selected alternative, or cycle back to one of the first three steps. In each of the first three steps, multiple pathways are possible.

3. OVERVIEW OF CHAPTERS

The volume includes four parts and 13 chapters. The 1st part is introduction and contains only chapter 1. The 2nd part is about a variety of computer technologies and their applications in forestry. There are seven chapters in this part. The 3rd part includes chapters 9-12, which introduce three comprehensive case studies. The last part summarizes implications of computer technologies to digital forestry.

Chapter 2 provides an overview of the application of optical remotely sensed data that has sufficient resolution to resolve overstory individual trees. Using such tree-scale data it is possible to detect the trees, delineate their outer canopy boundaries, detect internal canopy structures, identify the species type, and infer health or mortality information. In addition, it is possible to scale up to more traditional, stand-level data, while still retaining the individual tree-based information.

Chapter 3 focuses on a new generation of high-resolution, active remote sensing technologies, including airborne laser scanning (LIDAR) and interferometric synthetic aperture RADAR (IFSAR), which have the capability to provide direct, three-dimensional measurements of forest canopy structure and topography. The basic principles of active remote sensing technologies in the context of forest canopy inventory and terrain mapping are presented in their application within a Pacific Northwest conifer forest.

Chapter 4 considers some general aspects of forest information systems. The nature of information is discussed. A forest information system will comprise at least the components input, analysis, estimation and prediction, decision support, presentation, and visualization. With respect to information needs, a typology of information systems is presented. Information systems utilize the entire spectrum of computer sciences and computer technology. Methodological concepts are presented in the context of the different categories of information systems.

Chapter 5 is about road and harvest planning and operations that are undergoing rapid changes with improved access to terrain and vegetation data, advancements in computer algorithms, computer hardware and communications. Key technologies are LIDAR, global positioning systems (GPS), GIS, development of powerful optimization techniques, smaller and faster computers, larger and faster available computer memories, and availability of wireless communications.

Chapter 6 reviews and compares four major types of forest simulation models: (1) growth and yield models (empirical approach), (2) succession models (empirical–mechanistic hybrid approach), (3) process models (mechanistic approach), and (4) hybrid models. Their applications are described in four case studies. There is still a gap between foresters and ecologists in developing and using forest simulation models. Diversified modeling approaches need to be integrated into a decision–support system.

Chapter 7 summarizes a variety tools for visualization and their integrations with spatial data in forest planning and management, describes advances in computer graphic capabilities and enhanced functionalities of GIS that have advanced the use of visualization and spatial data analysis, demonstrates the applications of visualization in measuring and depicting impacts of management actions, predicting responses of the forest to different forest operations or intervention strategies by using 3D visualization with spatial data.

Chapter 8 introduces several major classes of software technologies that have been used in decision making for forest management applications over the past few decades. They include optimization, expert systems, network models, multi-criteria decision making, and integrated systems. Several example DSSs highlight the incorporation of these various technologies for vastly different management problems. Likely future development trends for decision support technologies over the next few decades include: Internet implementations, agent-based applications, increased social science components, and participatory decision making.

Chapter 9 reviews a variety of models developed in the United States and used for describing markets for forest products and trends in resource conditions. More complex models developed in recent decades provide the basis for forecasting future resource and market trends and inform policy analysis. These models have also extended options for policy analysis using approaches such as scenario planning to help decision makers gauge uncertainty.

Chapter 10 outlines the types of spatial datasets that are currently available to map fuels and fire risk, provides examples of how GIS has been applied in the Wildland-Urban Interface (WUI), and suggests future directions for the integration of GIS datasets and spatial models to support forest management in the WUI. Remote sensing and GIS technologies are crucial in this regard, but they must also be integrated with field surveys, fire behavior models, and decision support tools to carry out risk assessments and develop management plans for the WUI.

Chapter 11 introduces a digital system that links a number of computer tools including data collection, growth and yield simulations, a decision support system, and activity scheduling for sustainable forest management at Tillamook State Forest, Oregon, USA. The core of the computer tools is a spatial harvest scheduling model that simultaneously schedules timber harvest, forest structure, and transportation at the landscape scale. Post-processing tools are used to verify that the scheduling model is following the rules correctly and that the results are computationally correct.

Chapter 12 summarizes opportunities and challenges in China’s forestry systems, introduces the applications of geospatial and modeling techniques in forest inventory, harvesting, restoration, and protection with case studies in northeast China, and explains how these computer applications are systematically achieved with a decision-support system FORESTAR®.

Chapter 13 is intended to conclude the volume by introducing a simple process model that represents the classic process of getting from data about the forest to management actions; describing the drivers of digital forestry with a gear train, explaining the procedures of forestry digitization, and discussing the implications of digital forestry.

4. GOALS AND OBJECTIVES OF THIS VOLUME

As just outlined in the previous section, Part II of this volume presents eight chapters that span the array of major computer-based technologies in contemporary forest management. Certainly, other topics could have been included, but we believe the eight topics covered can justifiably be considered the core set of digital forestry. Our basic goal, following up on the 1st International Workshop on digital forestry, is to lay a firm foundation for the concept of digital forestry, and, in doing so, build a better foundation for the implementation of sustainable forestry. Two specific objectives supporting this goal, and relevant to Part II in particular, include:

(1) Reviewing the state of the art in each topic, and
(2) Within each topic, promoting a better understanding of how information flows into and out of the systems.

With respect to the first objective, we hope that practitioners in the respective fields will find these reviews a handy reference, and we expect that these reviews will also provide a good introduction to new students of a particular discipline. It is also worth pointing out that this is the first treatment to attempt such a broad review of so many disciplines in a single volume. However, the primary audience for each chapter is *not* so much the practitioners or students in the associated field, but, instead, their colleagues in *other* digital disciplines. Our premise is simple: better collaboration among the interrelated disciplines will enable more effective and efficient implementation of sustainable forestry. The second objective builds on the first, considering as explicitly as possible how information flows among systems can enable collaboration.

Our third objective is to provide practical demonstrations of how disciplines have collaborated through either the collaborative application of technologies or, in some cases, actual integration of technologies. This is the intent behind the chapters of part III. After all, it is relatively easy to talk about collaboration and integration; actually collaborating or integrating is much more difficult. So, we felt we would be remiss, if we neglected to present at least a few real-world examples.

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PART II

CORE TECHNOLOGIES

Chapter 2

HIGH-SPATIAL-RESOLUTION REMOTE SENSING

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Abstract: Recent developments in high-spatial-resolution remote sensing have created a wide array of potential new forestry applications. High spatial resolution imagery allows a tree-scale of analysis, in which individual trees and their attributes are the focus of interest. This tree-scale remote sensing contrasts with the traditional community-scale remote sensing of medium resolution sensors such as Landsat. A variety of approaches have been developed to identify individual trees and delineate their boundaries, including the association of tree tops with local image maxima, delineating edges of trees by focusing on the darker, shadowed areas, recognizing the brighter regions as image segments, matching image chips, or templates, to the individual trees, and mapping the tree shapes in three dimensions. Attributes used in assigning each tree polygon to a single species may include spectral or spatial features. Forest health and mortality can be quantified on the basis of the impact on individual trees, thus supporting improved monitoring and management of forests. Tree information identified in high resolution imagery can also be used to scale up to the stand level, and stand boundaries and attributes can be predicted with high levels of accuracy. As the underlying imaging and analysis technology improves, high-spatial-resolution remote sensing is likely to become a core component of digital forestry.

Key words: High spatial resolution; tree scale; individual tree; tree crown; species mapping; forest health; mortality; stand mapping; remote sensing.

1. INTRODUCTION

High-spatial-resolution remote sensing, using imagery with a pixel size of 1 meter or less (Hill and Leckie 1999), offers new opportunities for forestry

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applications. Most importantly, high-spatial-resolution data allows the transition from analysis at the forest community scale to the individual tree scale. Thus, the nature of the forestry applications that can be addressed with high-spatial-resolution remotely sensed data is potentially fundamentally different from that of medium-resolution data, such as the Landsat Thematic Mapper, with its 30 meter pixel size (McGraw et al. 1998). Medium-resolution data can provide only summary information on multiple trees, whereas with high-spatial-resolution data it is possible to study the fundamental forest unit, namely the individual tree.

High-spatial-resolution forestry remote sensing draws on two traditions. The first is aerial photography, which has been a mainstay of forest survey techniques for more than half a century (Lund 1997). Most forestry high-spatial-resolution projects still use imagery acquired from aircraft, rather than satellites. One advantage of aerial imagery is the potential to obtain higher spatial resolution. Even Quickbird imagery, with 0.67 meter pixels that provide the highest spatial resolution obtainable from current commercial satellites, is still marginal for many tree-scale applications. Although clearly the optimal spatial resolution is dependent on the size of the trees in the image, typically a pixel size of 0.5 meters or smaller has been found necessary for individual-tree remote sensing in mid-latitude and boreal regions (for example, see Lévesque and King 2003).

high-spatial-resolution remote sensing, however, differs from traditional aerial photography in that the data and analysis is digital and quantitative, instead of analogue and interpretative. With high-spatial-resolution remote sensing, the data is usually acquired in a digital format, although occasionally aerial photography is scanned to provide the digital data (e.g. Erikson 2004a). An important innovation supporting the transition to digital analysis of aerial imagery has been the development of global positioning systems (GPS) (Mostafa 2005) and innertial navigation systems (INS). GPS and INS allow very precise estimation of the location and orientation of the sensor aquiring the imagery, thus facilitating automatic georeferencing of the aerial imagery.

The second tradition exploited in high-spatial-resolution forestry remote sensing is that of digital image processing, including both satellite image analysis and machine vision applications. It is precisely because high-spatial-resolution data allows a focus on the object of interest, a single tree, rather than the arbitrary pixel, that the analysis of such data incorporates elements of machine vision, and not just traditional remote sensing techniques. Indeed, object-based analysis is one of the themes of this chapter.

The remainder of this chapter, following this introductory part, provides an overview of remote sensing applications in forestry at the individual-tree scale using high-spatial-resolution data. The second section deals with the identification of trees in images, which includes both the detection of trees, and the delineation, or localization (Pollock 1996), of the tree boundary. The third section describes approaches to identifying the species of each delineated tree, and this is followed in section four by a discussion of the generation of stand maps from remotely sensed individual-tree data. The fifth section is an overview of research on monitoring tree health. The chapter concludes with a discussion of future directions and issues, including the possibility of integrating imagery with LIDAR data. LIDAR, another new tradition in remote sensing which is having a revolutionary impact on forestry, is the subject of the next chapter in this book.

2. TREE DELINEATION APPROACHES

In an image of a closed canopy forest, individual trees are normally characterized by a distinctive pattern of relatively bright areas, surrounded by darker areas (Figure 2-1 Left, Figure 2-2 Left, and Figure 2-3 Left) (Plate 2-3 Left). The brighter area is a result of direct solar illumination of the canopy, and the darker areas are the surrounding shadowed regions. If the image brightness values are thought of as elevations, then the pattern associated with each tree would be represented by a convex mound (Gougeon 1995a), or blob. This simple blob model can be used to understand most of the common tree delineation methods:

- Local maxima methods that search for the "top" of the convex mound, which usually corresponds to the sun-lit top of the tree.
- Boundary-following approaches that identify tree edges generally within the shadowed regions between trees.
- Region-based segmentation approaches that identify groups of brighter pixels.
- Template matching methods use three-dimensional geometric models of trees, for example, cones, ellipses and cylinders, to generate synthetic two-dimensional images of the models, which are then correlated with the original image.
- Model-based methods in three dimensions generate summary shape parameters of trees from stereoscopic views.

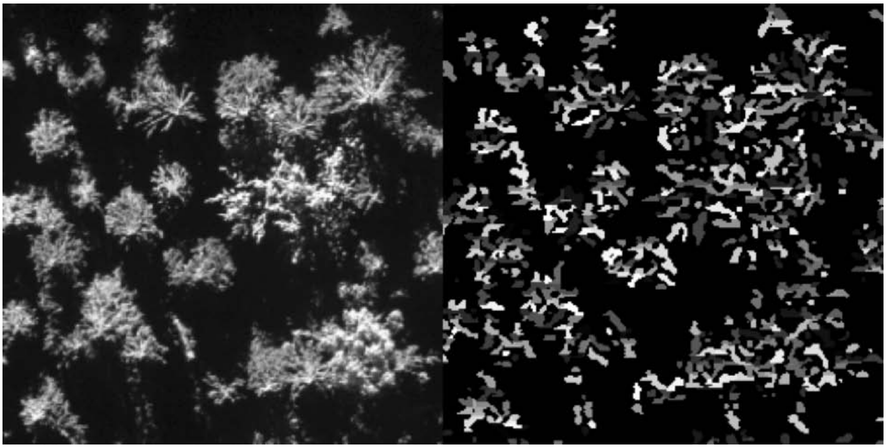

Figure 2-1. Left: High-spatial-resolution aerial photograph, with a 10 cm pixel size, of a mixed boreal forest. Right: Automated identification of linear tree crown structures that are associated with individual tree branches. (Reprinted from *Fuzzy Sets and Systems*, Vol. 132, T. Brandtberg, Individual tree-based species classification in high-spatial-resolution aerial images of forests using fuzzy sets, pp. 371-387, Copyright 2002, with permission from Elsevier.)

Figure 2-2. Left: Multi-detector Electro-optical Imaging Sensor (MEIS) 31 cm pixel image of part of the Hudson Plantation at the Petawawa National Forestry Institute, Ontario, Canada. Middle: Initial results of applying a valley-following program to identify trees. Right: Final results after applying a rule-based crown delineation program, which modifies the initial crown delineation results, for example by separating segments that have deep embayments. (Reprinted from *Canadian Journal of Remote Sensing* Vol. 21, F. A. Gougeon, 1995. A crown-following approach to automatic delineation of individual tree crowns in high-spatial-resolution aerial images, pp. 274-284. Used with the permission of the Canadian Aeronautics and Space Institute.)

The five methods listed above are dealt with individually in more detail in the rest of this section. However, it is important to note that many approaches are hybrids. For example, a local-maxima approach may be used to identify tree locations, and then a region-based method used to delineate the individual trees.

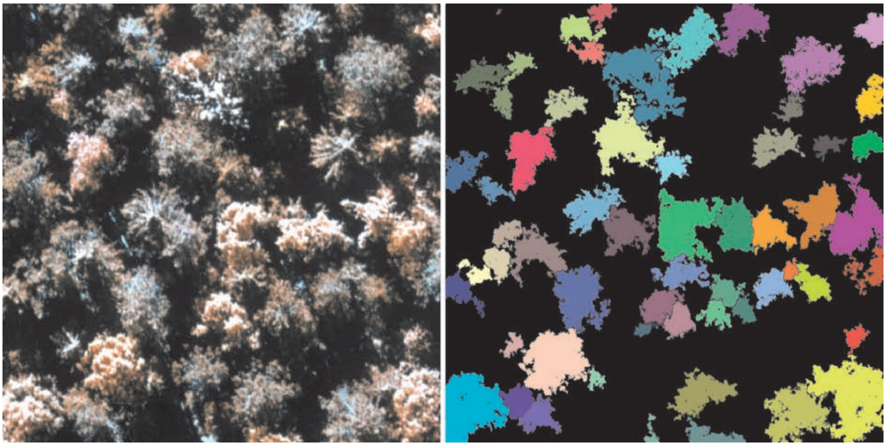

Figure 2-3. High-spatial-resolution aerial photograph and associated segmentation of individual tree crowns using a random walk approach. (Reprinted from Segmentation and classification of individual tree crowns in high-spatial-resolution aerial images, *Acta Universitatis Agriculturae Sueciae Silvestria* 320, Doctoral Thesis by M. Erikson, Swedish University of Agricultural Sciences, Uppsala, Sweden. Copyright 2004. Used with permission of the author.) (See also color plate 2-3 on p. CP1)

Delineating individual trees in high-spatial-resolution imagery varies from the very simple to highly complex, depending on the structure and species of the forest. For example, even-aged, single-species plantations are usually characterized by images with distinct and relatively uniform individual trees, whereas in images of naturally regenerated, uneven-aged, mixed-species forests, the trees are typically highly variable in size, shape and spectral properties. Multi-layered stands, for example stands with emergent overstory crowns, cause particular difficulties.

In high-spatial-resolution images, branches and irregularities within the crowns may be visible. Images with trees of varying canopy size, a common feature of naturally regenerating mature forests, are a particular challenge for tree identification because a single bright blob could represent a branch, a single tree, or a group of trees. On one hand, this complexity is a source of error, because it adds variability to the representation of the tree. On the other hand, the tree morphology may be sufficiently distinctive (Figure 2-1) that a trained human interpreter can use this information to detect and delineate individuals (e.g. Brandtberg 1997; 2002, Pollock 1996). However, computer-based tree identification requires high-level algorithms to exploit such complex spatial information, and may be less accurate than a human interpreter (Pollock, 1996). Indeed, for a number of studies on tree species or health mapping, topics that are covered later in this chapter, manually delineated polygons representing individual trees are used either as reference data (Warner et al. 2006), or as a way to reduce error in the analysis (Gougeon 1995b).

2.1 Local-maxima approaches

The simplest group of tree-detection methods assumes that a local maximum in the image corresponds to the top of a tree. Blazquez (1989) developed an early example of such an individual tree counting approach for citrus trees in Florida, using digital aerial color-infrared (CIR) photographs. His method included the identification of the *x*,*y* locations of local intensity peaks, as well as the associated crown perimeter, area, and mean intensity. Blazquez (1989) encountered many of the problems that also challenge studies of natural forests, including the issues of separating trees that appear as a single unit on the image, dealing with shadows, and radiometric normalization between photographs.

The top of the tree in an aerial image is usually displaced relative to the trunk, due to parallax and off-nadir viewing. Thus, if the tree trunk location is a desired attribute, perhaps for inclusion in a geographic information system (GIS), a correction should be applied. For example, Dralle and Rudemo (1997) incorporated the angle to the sun, camera position and estimated tree heights, in estimating the true stem locations from the positions of the local maxima. They found their method reduced the root mean square error (RMSE) to approximately only 65 cm when applied to images of homogenous stands of Norway spruce.

The identification of trees by searching for local maxima is affected by spurious bright pixels that are not part of larger bright blobs. An effective method for dealing with this problem is to convolve the image with a Gaussian kernel. A Gaussian kernel has weightings within the convolution mask that follow a Gaussian function. Thus, the smoothing function gives greater weighting to nearby pixels compared to those that are distant from the kernel center. The region over which the Gaussian kernel extends, and thus the scale of the smoothing, is determined by the distance in pixels that represents one standard deviation of the Gaussian function.

The smoothing scale directly affects the number of local maxima identified, and also causes a rounding-off of the brightness values of the edges of the tree crowns. Thus, selecting the optimal scale is a crucial question in local-maxima approaches. Dralle and Rudemo (1996) proposed a method to identify the appropriate scale based on the results of smoothing at different scales, and a comparison with field plot data of the number of stems actually present. They demonstrated the success of such an approach using a test site in Denmark, which has a range of even-aged Norway spruce stands and varying thinning treatments.

An alternative preprocessing convolution kernel is the Laplacian-of-Gaussian (LoG), which combines the Laplace operator and Gaussian smoothing. The Laplacian is based on second-order spatial derivatives, and therefore highlights locations where the image intensity varies rapidly.

Uttera et al. (1998) demonstrated the use of a LoG operator to segment individual trees in an image from southern Finland. They used two different approaches to choose the size of the LoG operator: (1) the crown diameter from visual interpretation of the image, and (2) field information about the number of trees per unit area in each plot. Wang et al. (2004) also used the LoG-operator as a preprocessing step to detect individual trees in a Compact Airborne Spectrographic Imager (CASI) image from British Columbia, Canada. They developed a two-stage procedure, with edge-detection followed by marker-controlled watershed segmentation. As with similar studies, the treetops were assumed to be represented by local maxima, near the centroid of the tree crown.

Obviously, the local-maxima approach will produce commission errors when applied to portions of an image where trees are not present. Thus, Lowell (1998) developed additional spectral tests to exclude shadows and road areas. Pitkänen (2001) compared different approaches for masking the non forested areas of the image, a process which he termed binarization.

As one of the simplest methods of tree identification, the local-maxima approach can be applied to relatively coarse-scale imagery, where the pixel size is not much smaller than the size of the individual tree. For example, Wulder et al. (2000) found that with 1 meter pixels, tree crowns as small as 1.5 meters could be identified. Wulder et al. (2000) also point out that variable window-size techniques reduce detection errors, since the optimal window size varies with tree size.

The application of the local-maxima approach to broad leaf forests has, not surprisingly, been found to be less successful. For example, Lowell (1998) tested a local-maxima algorithm on an even-aged, 60 year old, Eucalyptus forest in southern Australia with comparatively disappointing results. Furthermore, he found that tree height from photo-interpretation was more important for estimating log volume than image derived attributes.

2.2 Boundary-seeking approaches

An alternative to the local-maxima approach, which identifies tree tops from a search for the locally brightest pixels, is to identify the boundaries directly, focusing on the shadows between individual trees (Gougeon 1995a, Warner et al. 2006). When a topographic analogy is used to describe the surface of brightness values, the tree boundaries are represented by valleys, hence the term valley-finding approach for one implementation of this approach (Gougeon 1995a).

In the valley-finding method (Gougeon 1995a; Leckie et al. 2005b), local minima are identified in the image. The algorithm then tries to connect these minima along image brightness valleys, but terminates if the brightness value is above a threshold (Figure 2-2 Left and Middle). Subsequently, the crown boundaries are extended in a clockwise direction to try to close the loop around each individual tree (Figure 2-2 Right). In a variant of this method, Warner et al. (2006) use a minimum-cost-path approach for connecting the local minima.

The curved boundary of a single tree can be used indirectly to delineate the tree crown and to estimate its crown size and stem position (Brandtberg and Walter 1998; Brandtberg 1999). In this approach, curved edge segments are treated as individual objects that are closely related to the single trees. The curved segments can be used to model the tree crowns at multiple scales. This object-oriented approach provides a method to determine the optimal scale of Gaussian smoothing, since smoother edge segment shapes are more likely to indicate the correct location of the tree. The boundary-seeking approach can also be used to estimate the degree of crown overlap between neighboring trees and to estimate statistically the number of stems per unit area (Brandtberg 1999). However, an evaluation of stem diameter predictions in naturally regenerated forests in central Sweden using this approach indicated that the accuracy was dependent on the species present. In particular, the stem diameter of Norway spruce was extremely difficult to estimate, since that species appeared to be obscured by shadows to a much more variable degree than Scots pine, birch, and aspen. Furthermore, spruce is not always depicted in the image as a compact circular object; instead it sometimes is more linear and elongate. These types of problems can often be accommodated by human interpreters, but this is less easy when using computer-based methods.

2.3 Region-based segmentation

Region-based tree segmentation is the direct search for a group of pixels that likely represent a single tree. Some algorithms combine an initial local-maxima detection methodology with a subsequent region-based approach. For example, Pinz et al. (1993) identified local maxima as candidate tree-center points within a series of low pass filtered images. The region surrounding each local maximum was then sequentially tested for the radial brightness distribution pattern that is characteristic of trees. This combined approach detected more than 90% of the trees in a dense forest in Austria. Pouliot et al. (2002) also used a combined local maxima and radial brightness approach. In their study, the boundary of the tree segment is defined as the point of maximum rate of brightness change. Their method was found to detect 91% of the trees, and estimate crown diameters to within 18% of field measurements, based on a test site of coniferous forest regeneration in Ontario, Canada. The trees at this site were very small, with a crown diameter of approximately 1 meter; the pixel sizes in their study varied from 5-30 cm.

Erikson (2003) used a region growing approach to segment single tree crowns in aerial photographs from a mixed-species boreal forest in central Sweden. Erikson's (2003) region growing starts at single pixels, which represents seeds, and grows out to include adjacent pixels that fall within spatial and spectral thresholds. The single best segment obtained for each position is used to represent the tree crown. In an evaluation of this approach, approximately 73% of the segments agreed with the manual delineation, and the estimate of the total number of stems was within about 93% of the manual count obtained from interpretation of the aerial imagery. Figure 2-3 (Plate 2-3) shows an example where Erikson's (2003) algorithm has been further modified using random walk as a region growing process (Erikson 2004b).

Culvenor (2002) developed the Tree Identification and Delineation Algorithm (TIDA), which uses the local radiometric maxima and minima to indicate the likely locations of tree centroids and boundaries, respectively. The minima are used to create a network between the tree crowns, which is subsequently used to restrict a clustering process that identifies crown pixels. TIDA is thus clearly a hybrid approach. It was developed for, and tested on, Eucalypt forests in south-eastern Australia. The best results were found in even-aged, pre-mature forests, where the trees still have a conical upper canopy shape.

The issue of identifying trees of varying size has already been mentioned above. Brandtberg et al. (2003) proposed a multiscalar solution to this problem, based on scale space theory. Brandtberg et al. (2003) based their approach on blob detection, or the identification of convex regions in the image brightness surface. The blob detection is conducted at multiple scales, using all local maxima, at each scale, as seed points. The support regions of the blobs are grown simultaneously, until no more nearby convex local patches can be found. The blob at each image location with the strongest scale-invariant blob signature measure (i.e. local contrast) within a scale-interval is then selected. Thus, this method uses a spatially varying, blob-based approach, to control the scale of Gaussian smoothing. The detected image structures are subsequently used as single objects in an image restoration algorithm to eliminate the effect of vignetting, the brightness fall-off towards the edges of the aerial image. The method was tested on imagery of leaf-on deciduous trees, comprising mainly native oaks, maple, and tulip-poplar, in West Virginia, USA.

2.4 Template matching

Template matching usually employs an optical crown model to generate synthetic image chips that represent individual trees (Pollock 1996, Larsen and Rudemo 1998). The crown model incorporates the variables that are assumed to control the variation of representation of trees in the image, typically including information on the tree geometry (size and shape), as well sun and view angles. Thus, the template used may vary with location across the image. The correlation between the template, or synthetic image (Figure 2-4), and a corresponding area of the real image is calculated sequentially for each pixel location in the image. The resulting correlation image depicts local maxima where the templates fit the remotely sensed data relatively well, and thus represent likely locations of trees. One drawback to this approach is that a wide variety of templates may be required, unless the trees are very uniform.

In an evaluation using 340 sample trees, Pollock (1996) found that the false detection of trees, or commission error, was about the same (10-11%) for his automated template matching approach as the error observed for human interpreters. However, the number of trees that were missed, in other words the omission error, was quite different for the automated and manual methods. The template matching method missed 38% of the trees, whereas the manual interpretation missed only 14%, thus emphasizing the superior skills of human interpreters when applied to complex forest scenes. For example, the template-matching approach was weak when the hardwood trees had irregular crown forms, formed tight groups of trees that were mistaken as big single trees, and when big trees partially occluded neighboring smaller trees. However, the accuracy of the estimation of the crown diameter was similar using the automatic and manual methods, and was relatively consistently underestimated, since the full crown area was usually not visible in the imagery.

Larsen and Rudemo (1998) extended the Pollock (1996) template approach to include a background surface against which the tree crown is modeled as a generalized ellipsoid made up of needles and branches (Figure 2-4). Their approach uses template matching to estimate the optimal size, shape and placement of the crown ellipsoid along the tree trunk. They evaluated the performance of the optimization on side- (Figure 2-5), backand front-illuminated individuals of spruce trees in Denmark, and found satisfactorily results. The standard error for the tree top position estimates was 25-30 cm, while the tree recognition accuracy was 91-98%.

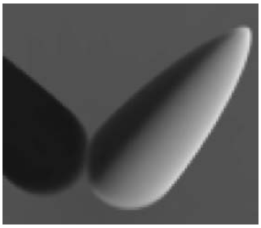

Figure 2-4. The single tree optical model used for the side-illuminated trees in Figure 2-5. (Figure copyright M. Larsen, and used with his permission.)

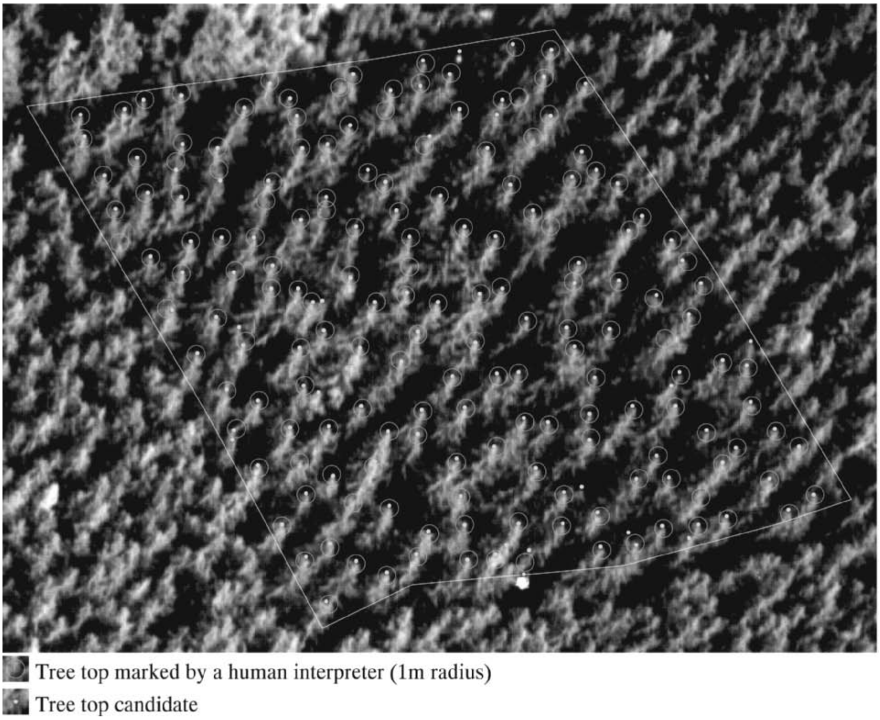

Figure 2-5. Side-illuminated individual Norway spruce trees with the result of template matching marked as automatically and manually detected treetops. (Reprinted from *Pattern Recognition Letters*, Vol. 19, M. Larsen and M. Rudemo, Optimizing templates for finding trees in aerial photographs, 1153-1162, Copyright 1998, with permission from Elsevier.)

2.5 Model-based approach in 3D

In concluding their report on template matching, Larsen and Rudemo (1998) discuss how stereo methods might improve their optical model. Gong et al. (2002) describe such a 3D model-based approach using stereo pairs, in which the problem is defined as an optimal tree model determination issue. The individual trees are modeled as hemi-ellipsoids with a total of seven parameters: tree top location in 3D, trunk base height, crown depth, crown radius, and a coefficient for crown curvature of the canopy envelope. This semi-automatic approach was tested on stereo pairs of a closed redwood stand in California, USA. The reported overall accuracies were 94% and 90% for tree height and crown radius, respectively.

3. IDENTIFYING SPECIES

High-spatial-resolution imagery can be used not only for tree delineation, the subject discussed in the previous section, but also for identifying the species of individual trees. To some degree, the identification of species type may seem to be a traditional remote sensing application, and therefore a problem that can be addressed using standard remote sensing techniques (Carleer and Wolff 2004). However, there are important differences between remote sensing using high-spatial-resolution imagery and moderate-spatial-resolution imagery, such as Landsat. The tree scale of high-spatial-resolution imagery suggests that classification may potentially be simpler, in the sense that the classes that may be identified are individual species, rather than communities of species, as with moderate-resolution imagery. On the other hand, spectral classification of high-spatial-resolution imagery using per-pixel methods developed for moderate-resolution imagery can result in surprisingly low accuracies (Franklin et al. 2000). One major reason for this is that as the spatial resolution increases, heterogeneity within the class of interest may increase. For example, varying illumination, percentage shade, and proportions of background and tree components, such as bark and leaves (Meyer et al. 1996), as well as variation in pigments, flowering, or phenology within the tree (Asner 1998), may all result in a broadening of the range of spectral values associated with a particular species.

Much of the early work on the remote sensing of individual trees was carried out on even-aged coniferous forests, with only a small number of species. Extending this work to more complex forests, and forests with more species, has proved a challenge (Warner et al. 2006). Clearly, increasing the number of species in a classification increases the potential for error. Furthermore, classification accuracy varies by species, and therefore the accuracy that can be expected will vary based on the forest composition itself (Leckie et al. 2005c) and the hierarchical level of detail that is mapped (Gerylo et al. 1998).

Leckie et al. (2005c) investigated a range of issues associated with high-spatial-resolution multispectral remote sensing of an old-growth forest in central Vancouver Island, British Columbia. They found wide variablity and overlap in the spectral properties of the different species. To try to reduce the effects of variability, they established multiple spectral classes for each species, and unhealthy and shadowed trees were treated separately, or not classified at all. Leckie et al. (2005c) point out that in structurally complex forests, the specific trees that are visible vary depending on illumination and viewing angles. Thus, the observed trees in an image will not include every tree actually present, thus adding complexity to the interpretation of the results.

3.1 Spectral features and tree polygons

The obvious solution to dealing with the high variability of spectral values within each tree species is to aggregate the information within a spatial unit comprising several pixels. In an early, classic work, Kettig and Landgrebe (1976) showed that even with moderate resolution data for mapping broad land cover classes, an increase in both processing time and accuracy could be achieved by grouping spectrally similar adjacent pixels, and classifying each group as a unit.

For forestry applications, it is intuitive that the most appropriate spatial unit will generally be the individual tree. Ideally the tree boundaries might be identified through automated means, thus facilitating the application of the method to large areas, but it is also possible to use manually digitized polygons (Meyer et al. 1996, Gougeon 1995b). Warner et al. (2006) found that even polygons produced through automated methods that were only partially in agreement with detailed ground mapping improved tree species classification.

Gougeon (1995b) systematically tested seven approaches for classifying polygons based on the spectral properties of the constituent pixels. His list of polygon spectral features ranged from the simple to the complex. The simple features comprised the mean of the pixels within the polygon, the mean of the brighter, sunlit pixels in the polygon, and the selection of the brightest pixel to represent the whole polygon. The more complex features attempted to capture second order statistics of the pixels within the polygon, for example he used the covariance matrix, principal component analysis (PCA) features, and features derived from the regression of each band against the near infrared band. Warner et al. (2006) found that post-classification assignment of the most common species within each polygon to the entire polygon resulted in a higher accuracy than classifying the entire polygon based on the mean spectral response of the pixels within the polygon, or classifying each pixel independently.

In summarizing his results comparing the seven sets of spectral features for classification, Gougeon (1995b) makes two interesting points. The first is that classification with the simple features, especially those based on the mean of the pixels and the mean of the brighter pixels, generally resulted in higher accuracies than classification with the more complex features. Secondly, Gougeon (1995b) found that, in replicating the classifications 10 times using different samples to train and test the classification each time, 20 percent or more variation in accuracy was observed. This suggests that analyst experience in selecting appropriate pixels for developing training statistics may be as important as the features used, or the classification algorithm.

3.2 Spatial features

In addition to spectral features, it is also possible to employ texture and other spatial properties to improve spectral-classification accuracy. Spatial features are central to the human process of visual interpretation, and Fournier et al. (1995) have developed a comprehensive catalogue of discriminators for visual interpreation of species. Automating the recognition of spatial features for image classification has, however, proved much more difficult. In some cases, when texture is tested systematically, it is found not to add information beyond that of the spectral bands (Leckie et al. 2003b). Part of the challenge is the difficulty in selecting both the scales over which to calculate spatial features and the method of calculating the spatial features. A wide range of generic spatial features has been proposed; the two most common are:

- First order statistics, such as the variance of the pixels within a moving window (Meyer et al. 1996) or tree polygon. Such methods are not influenced by the relative arrangement of the pixels within the local neighborhood.
- Second order statistics, such as the features derived from the gray level coocurrance matrix (GLCM) (Haralick and Shanmugam, 1974, Franklin et al. 2000), which depend on the spatial arrangement of pixels within the local neighborhood.

Brandtberg (2002) developed six spatial features to identify boreal tree species (Figure 2-1), which he used in addition to spectral properties. The spatial features consisted of a measure of concavity of the edge of the tree on the shaded side, the consistency of the direction of curvature of the outer contour of the tree, fine and coarse scale texture measures, a measure of the presence of a radial pattern, and the relative size of the crown. Brandtberg (2002) integrated these features using a fuzzy membership approach, a technique that is particularly useful for dealing with ambiguous datasets where individuals may have attributes associated with more than one category.

Erikson (2004a) developed spatial features specific for the identification of spruce and pine trees. He found that the solar illumination of the concially shaped conifers typically resulted in the brighter, sunlit pixels forming a crescent shape in the two dimensional image. He therefore developed a spatial metric for the tree delineations based on the ratio of the length of the boundary segments to the associated convex hull. Concave boundaries are longer than the convex hull, the polygon with the shortest boundary that encloses the tree.

3.3 Temporal information for classification

Key et al. (2001) note that high-spatial-resolution satellite data tends to have low spectral dimensionality. They therefore investigated whether multitemporal single band, panchromatic imagery can provide as much information as single date multispectral imagery. Although they found that an optimally timed multispectral image provided the greatest classification accuracy, multitemporal panchromatic images proved a close substitute. The significance of this finding is that a higher level of spatial detail may be obtained from the panchromatic images, and it can be very difficult to get imagery during the optimal times necessary if multispectral data is used.

4. DEVELOPING STAND MAPS

Stand maps generated from high-spatial-resolution data potentially provide much more valuable information than those generated from moderate-resolution data, because the underlying individual-tree data can be accessed even after the data is aggregated to the stand level. Thus, in addition to overall community composition, average crown size or number of stems per hectare can be calculated from the individual-tree delineations.

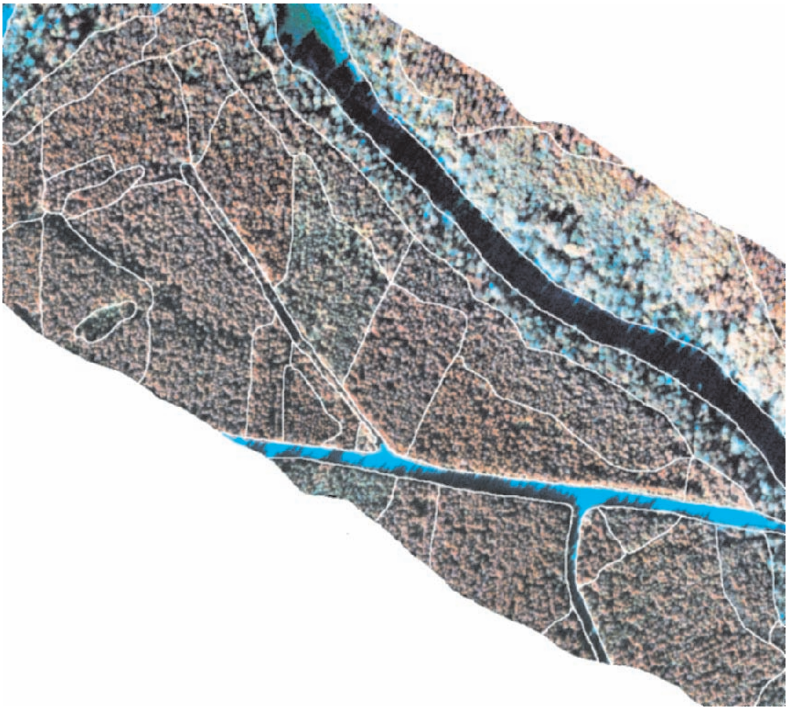

Figure 2-6 (top). Standard false color composite of Compact Airborne Spectrographic Imager (CASI) image of a forest near the Nahmint River, Vancouver Island, Canada. Stand boundaries, shown in white, were produced by manual interpretation of the imagery and stereo color photography. (Reprinted from *Remote Sensing of Environment*, 85, D. Leckie, F. Gougeon, N. Walsworth and D. Paradine, Stand delineation and composition estimation using semi-automated individual tree crown analysis, page 360, Copyright 2003, with permission from Elsevier.) (See also color plate 2-6 on p. CP1)

Leckie et al. (2003b) provide an excellent overview of an end-to-end application of high-spatial-resolution multispectral imagery for stand composition and delineation on the basis of mapping individual trees (Figures 2-6 and 2-7) (Plates 2-6 and 2-7). For this work, individual-tree crowns were isolated using the valley following approach of Gougeon (1995a). The crowns were subsequently mapped as one of five coniferous species or a general deciduous class. The crowns were then grouped using an unsupervised classification of stem density, crown closure, and species composition attributes. A sieve operation was used to remove polygons that were smaller than the minimum mapping unit area, and a smoothing operation applied to generalize the boundaries.

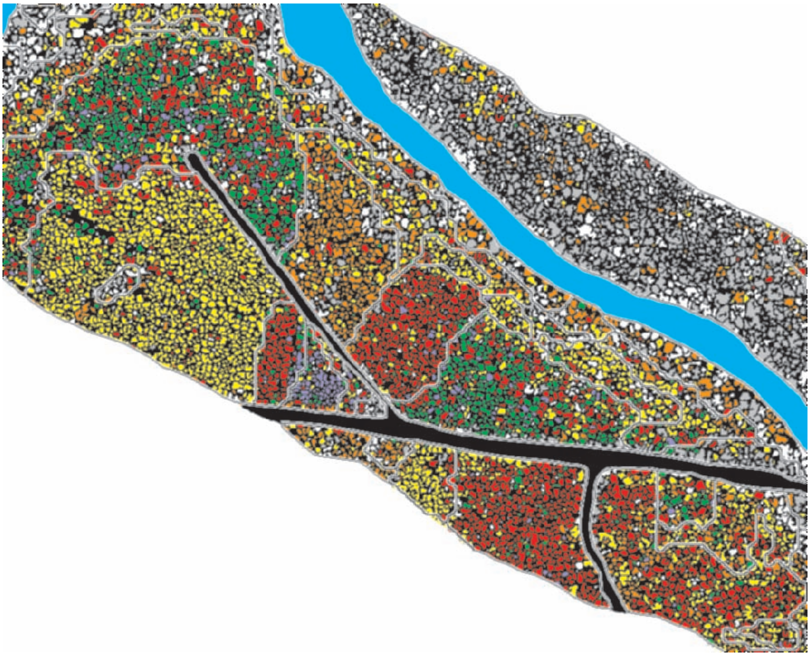

Figure 2-7 (bottom). Automated delineation of individuals, species classification and stand delineation. Douglas fir = red, grand fir = green, amabilis fir = blue, western red cedar = orange, western hemlock = yellow, hardwood = gray, and unclassified = white. (Reprinted from *Remote Sensing of Environment*, 85, Leckie, Gougeon, Walsworth and Paradine, Stand delineation and composition estimation using semi-automated individual tree crown analysis, page 361, Copyright 2003, with permission from Elsevier.) (See also color plate 2-7 on p. CP2)

5. TREE HEALTH

Tree health mapping ranks with species identification as one of the major applications of high-spatial-resolution imagery. A wide range of applications have been investigated, including the effects of general species decline (Yuan et al. 1991), pathogens (Kelly et al. 2004), insect defoliators (Leckie et al. 1992, 2005a) and stress from mine waste (Lévesque and King, 2003).

In some cases, classification of individual pixels, without spatial aggregation to the tree level, has been found to be effective. For example, Kelly et al. (2004) mapped hardwood mortality from the sudden oak death (*Phytophthora ramorum*) in California using a per-pixel hybrid supervised-unsupervised classifier. Likewise, Leckie et al. (2005a), using multispectral classification of comparatively coarse 2.5 meter imagery, mapped degree of crown discoloration caused by jack pine budworm. On the other hand, Leckie et al. (2004) used both manual and automated tree delineation in identifying individuals affected by laminated root rot (*Phellinus weirii*). This latter study found that excessive spectral variability between trees made differentiation of root rot symptoms difficult, and thus aggregating data to the tree scale was important in increasing the accuracy of their study.

Given the wide range of tree health applications that have been investigated, it is perhaps not surprising that no consensus has developed regarding the optimal spectral and spatial measures to use, or indeed whether spatial or spectral measures are preferable. Many studies use only spectral data, and Leckie et al. (2005a) has shown that for jack pine discoloration mapping, just two well placed bands (667 nm (red) and 780 nm (near infrared)) can provide good results. The importance of red and near infrared bands, the wavelengths used in many general vegetation mapping studies, has been confirmed in many other forest health studies (Leckie et al. 1992, 2004).

In contrast to spectral based studies, Yuan et al. (1991) found that a combination of spectral and texture based transforms provided the most accurate identification of sugar maple decline. Lévesque and King (2003), in their work mapping stressed vegetation, found little value in the original spectral band data. Instead they found that the geostatistical measure of semivariogram range and GLCM texture provided most of the discrimination between different forest canopy structure and health classes.

6. FUTURE DIRECTIONS AND ISSUES

High-spatial-resolution remote sensing for forestry application has reached a relatively mature phase, as can be seen by the wide range of applications discussed in this chapter. Nevertheless, a number of challenges and opportunities remain.

Clearly for the potential of high-spatial-resolution remote sensing to be realized, the image processing methods must be robust so that they can be employed in a routine fashion over wide areas without requiring extensive calibration and adjustment for each new area. Although relatively standard techniques can be employed with simple and relatively uniform forests, more complex forests still require customization of the analysis. This is particularly true for deciduous forests, as well as mature and old-growth forests.

In monitoring tree health with high-spatial-resolution imagery, most studies are characterized by a limited geographic extent, test sites that comprise relatively uniform forests, and methods that are empirical and require local calibration. Extrapolating forest health studies over wide geographic regions is a challenge because the added complexity of varying vegetation types can overwhelm the relatively weak signal associated with vegetation stress. One possible solution to this problem of complexity is to identify forest health change through multitemporal imagery, because it may be easier to identify stress from spectral change, rather than from the spectral properties of stress itself.

Hyperspectral data has traditionally been acquired at a moderate spatial resolution. However, high-spatial-resolution hyperspectral imagery may allow the direct mapping of species with much greater reliability (van Aardt and Wynne 2001) as well as the detection of pest infestation (Lawrence and Labus 2003) and physiological indications of stress, such as chlorophyll content or fluorescence effects (Zarco-Tajada et al. 2002).

It would be useful to be able to use satellite imagery, instead of aerial imagery for remote sensing of individual trees. Although the use of high-spatial-resolution satellite imagery is constrained by a limited global archive and high cost, satellite imagery has the advantage of a relatively uniform illumination and view angle over large regions, thus minimizing problems associated with mosaicking individual digital images or flight lines. Unfortunately, it seems that the 0.67 meter Quickbird and 1 meter IKONOS nominal pixel size is probably too coarse for many applications. One interesting exception is Clark et al. (2004), who demonstrate the identification of tree mortality in a tropical forest using IKONOS imagery. More typical, however, is the finding of Lévesque and King (2003) that 0.5 meter data was preferable to 0.25 or 1.0 meter data for their individual tree work. Thus, an important development for forestry remote sensing may be the possible launching of commercial 0.5 meter spaceborne sensors (Bates, 2000).

Although high-spatial-resolution data potentially provides tremendous detail on individual trees, the integration of this information with LIDAR data has potentially revolutionary impact (Coops et al. 2004, Blackburn 2002, Leckie et al. 2003a). For example, with LIDAR data, it is possible to measure tree structural attributes directly. LIDAR is the subject of the next chapter, where it will be discussed in more detail.

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Chapter 3

ACTIVE REMOTE SENSING*

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Abstract: The development of remote sensing technologies increases the potential to support more precise, efficient, and ecologically-sensitive approaches to forest resource management. One of the primary requirements of precision forest management is accurate and detailed 3D spatial data relating to the type and condition of forest stands and characteristics of the underlying terrain surface. A new generation of high-resolution, active remote sensing technologies, including airborne laser scanning (LIDAR) and interferometric synthetic aperture RADAR (IFSAR) have the capability to provide direct, 3D measurements of forest canopy structure and topography. High resolution LIDAR can be used to measure attributes of individual tree crowns composing the overstory forest canopy. In addition, metrics based upon the lidar height distribution are highly correlated with critical forest structure variables, such as dominant height, basal area, stem volume, and biomass. IFSAR is a microwave remote sensing technology that is also capable of providing 3D positions of backscattering elements within a forest scene. While IFSAR typically provides measurements of lower resolution and accuracy than LIDAR, it has an all-weather capability and is acquired at a much lower cost per unit area. In addition, the use of multiple-frequency RADAR systems allows for the collection of information on different scene components. For example, long-wavelength P-band energy penetrates through the canopy and reflects mainly from the terrain surface, while short-wavelength X-band energy reflects from the first reflective surface. Therefore, the difference between the X-band (canopy) surface measurements and the P-band (terrain) surface will yield vegetation height information. In this chapter, we will describe the basic principles of these active remote sensing technologies in the context of forest canopy inventory and terrain mapping, and present an example of their application within a Pacific Northwest conifer forest.

Key words: Interferometry; laser scanning, RADAR; accuracy; forest; vegetation; survey; lidar; IFSAR; DEM.

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1. INTRODUCTION

Forests are structured as complex systems in three-dimensional or 3D space. The 3D structural organization of the forest canopy and the morphology of the underlying terrain are critical determinants of light regime, micro-climatic variability, and soil characteristics that drive the functional processes of forest ecosystem dynamics (Spies 1998). Effective management of complex forest ecosystems for the provision of a diverse array of outputs, including high-quality habitat, clean water, commercial timber, and recreational opportunities, is dependent upon the ability to quantify and measure critical forest structure attributes and micro-scale terrain characteristics.

Accurate estimation and monitoring of these 3D forest attributes requires collection of 3D data (Andersen 2003). These data are typically collected using traditional stand examination and topographic survey techniques, and are expensive and labor-intensive to acquire. Due to the high costs, the sampling intensity of these field-based inventory programs is typically limited, making the estimates acquired over large, heterogeneous forest areas subject to sampling error. In contrast, remotely sensed data, acquired from either an airborne or spaceborne platform, are potentially cheaper and less labor intensive to acquire, and are spatially extensive, theoretically reducing sampling error. While it is widely recognized that forest structure information is needed over large areas of the United States to meet ecosystem management objectives, the application of remote sensing-based inventories has been limited in scope due the limitations of existing data, processing techniques, and methodology.

The main limitation of remotely sensed data acquired from a passively-sensed technology (such as an aerial camera or satellite-based imaging system) for the acquisition of forest structure and terrain information is related to the fact that the illumination geometry and intensity are not controlled, and that the analysis requires an inference from 2D to 3D. The formation of passive, remotely sensed imagery is dependent upon reflected solar radiation, and is, therefore, subject to the effects of shadowing and bidirectional reflectance, which by virtue of simple geometry severely limit the amount of light reflected back to the sensor from components beneath the canopy surface. Photogrammetric measurement techniques permit the acquisition of 3D information from overlapping 2D imagery (i.e. aerial photographs, high-resolution satellite imagery), but requires that measured points be identified as conjugate points either through manual stereoscopic viewing or application of automated image correlation algorithms. Given the myriad of geometric and illumination effects at play in the formation of a complex forest scene in passive imagery, it is very difficult to train an automated algorithm to correlate (and measure) imaged points on the irregular surface of the canopy, and impossible to measure points underneath the surface that are not imaged. While passively-sensed 2D images are an invaluable source of data on spectral reflectance properties within forest areas, they have limited utility for acquiring accurate information on the 3D properties of the canopy and underlying terrain surface.

2. ACTIVE, HIGH-RESOLUTION AIRBORNE REMOTE SENSING TECHNOLOGIES FOR PRECISION FORESTRY

The emergence of a new generation of active, high-resolution airborne remote sensing technologies in recent years, enabled by the concurrent development of precise geopositioning technologies such as differential global positioning systems (GPS) and inertial navigation systems, has given rise to a source of data that is particularly well-suited to the measurement of 3D forest attributes. Specifically, airborne laser scanning (LIDAR) and interferometric synthetic aperture RADAR (IFSAR) are not subject to the limitations of passively-sensed imagery described above. Small-footprint, discrete-return LIDAR sensing systems emit pulses of laser energy in a narrow beam, and record a coordinate for each laser reflection along a swath beneath the aircraft. LIDAR systems are characterized by actively-pulsed emission of radiation and highly-controlled illumination geometry, enabling the accurate, detailed measurement of reflecting surfaces (i.e. leaves, branches, stems) down through the full depth of the forest canopy. Research in recent years has shown that high-resolution, small-footprint LIDAR data can be used to extract highly detailed information relating to vegetation structure and terrain characteristics (Reutebuch et al. 2005).

IFSAR systems operate in the microwave portion of the electromagnetic spectrum, and rely upon different sensing principles than optical LIDAR technology. Relatively low-frequency microwave energy used in RADAR systems will physically penetrate the canopy volume, where the degree of penetration is a function of the RADAR frequency. RADAR systems also have the capability to penetrate through cloud cover, which can be a critical factor in acquiring data over areas of the world that are nearly perpetually overcast, such as the tropics. IFSAR data can be characterized as the result of an integrative signal processing procedure, where the 3D location and characteristics of an actively-sensed object or surface point are inferred from the combination of various signal responses associated with this scattering element. The collection of IFSAR at multiple frequencies allows for direct measurement of the geometry of the canopy and terrain surfaces, and can provide a powerful description of forest canopy structure. While the resolution of IFSAR systems cannot, at present, match that of LIDAR, the all-weather capability and lower cost per unit area of IFSAR data indicate that it will emerge as an economically viable option for large area forest survey applications.

The emergence of active, high-resolution, airborne remote sensing technologies has the potential to significantly improve the quality and detail of the spatial data available to the forest manager. In this chapter, we will describe the basic principles of these advanced active remote sensing technologies and discuss their application to forest inventory and terrain mapping.

3. PRINCIPLES OF AIRBORNE LASER SCANNING

Airborne laser scanning, also known by the acronym LIDAR (Light Detection and Ranging), is an operationally mature remote sensing technology that can provide highly-accurate measurements of both forest canopy and ground surface[1]. A LIDAR sensor system essentially works upon the principle of measuring the time interval between the emission and reception of laser pulses. Range measurement is performed by multiplying this time interval by the speed of light ($R = c \times t/2$ (where, R is the range, t is the time interval between emission and receiving the pulse, and c is the speed of light, a known constant: 3×10^8 m/s)).

The leading edge of the returning signal is not a well-defined point, so the time is usually recorded for a point at which the signal exceeds a certain threshold level, which is usually defined as a constant fraction of the signal peak (Baltsavias 1999). If the precise orientation and position of the laser is known from an inertial measurement unit and airborne differential GPS systems, respectively, the 3D vector corresponding to each laser pulse can be reconstructed, and a 3D coordinate assigned to each reflection. The "raw" LIDAR data are then typically provided as an ASCII or binary file

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[1] LIDAR systems are classified into two types, depending upon the size of the "footprint" for the laser pulse. "Small footprint" systems typically have footprint diameters of less than 1 meter, while "large-footprint" systems have footprint diameters greater than 10 meters. Given that large footprint, continuous waveform LIDAR systems are neither commercially available nor capable of providing high resolution data, in this chapter we will restrict our discussion to the use of small-footprint, discrete-return LIDAR data. The application of large footprint LIDAR to forestry applications has been discussed in Harding et al. (2001) and Lefsky et al. (2002).

containing X,Y,Z values corresponding to the coordinates of each laser reflection.

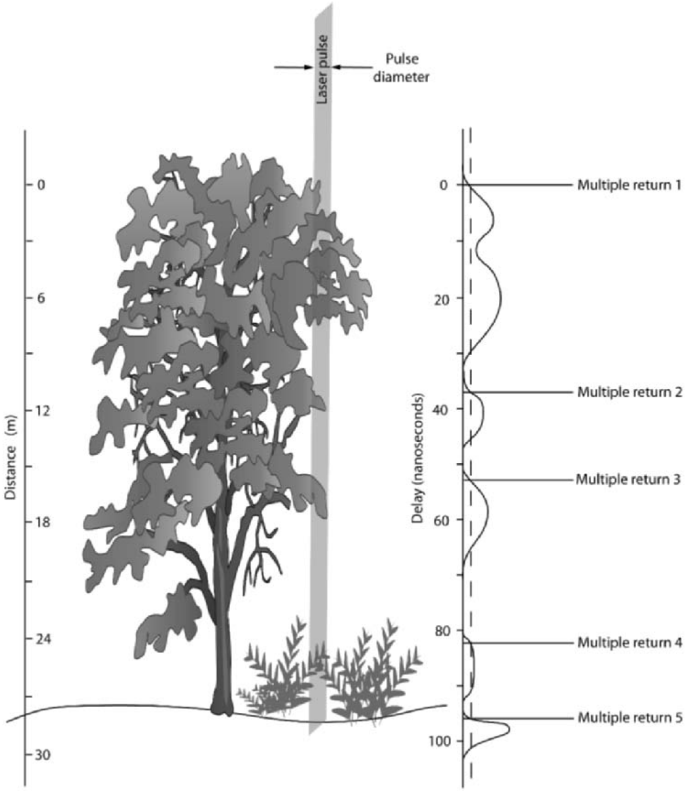

Figure 3-1. LIDAR remote sensing of vegetation. As the laser pulse passes through tree canopy, a signal is returned to the sensor. The leading edges of peaks in the returned signal correspond to multiple returns. Adapted from Lefsky et al. (2002).

The power received by the sensor will depend upon target characteristics, including the physical properties of the target (i.e. diffuse vs. specular reflector) and absolute target, reflectivity. LIDAR systems used for topographic mapping applications usually operate in the near infrared range of the electromagnetic spectrum (800-1100 nm). While specifications vary among systems, current LIDAR systems emit from 5,000-100,000 pulses per second, and vary the scan angle using optical-mechanical devices such as oscillating mirrors. Most systems have the capability of recording multiple reflections from a single laser pulse (i.e. up to 5 per pulse). For example, in a forest area a given pulse may reflect from branches or leaves within the vegetation canopy and the ground below (Figure 3-1). As the scan angle is usually limited to 15-20 degrees off nadir, this system acquires measurements along a “swath” beneath the aircraft (Figure 3-2). For airborne, small-footprint systems, the footprint, or spot size, of the LIDAR pulse when it reaches the ground (or canopy surface) ranges from 0.10-1 meter depending upon flying height. In forested areas, the energy from individual LIDAR pulses can penetrate through gaps, and can therefore provide measurements of the underlying terrain surface.

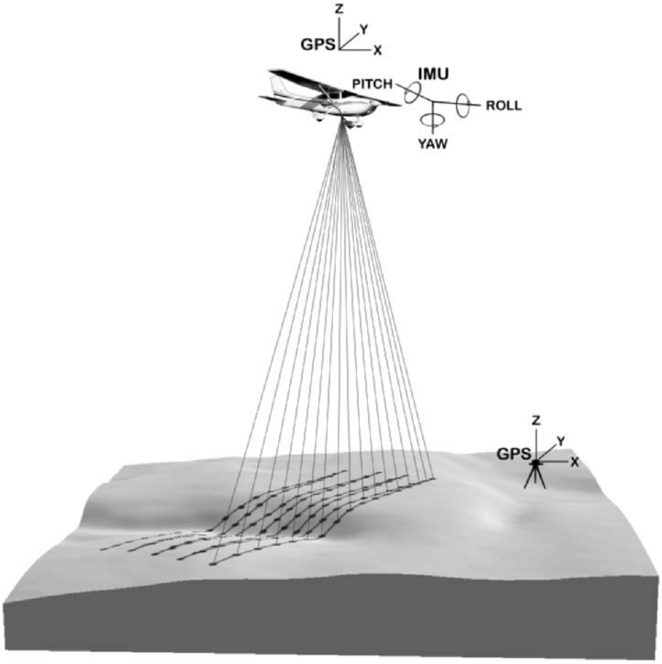

Figure 3-2. An illustration of airborne laser scanning.

4. LIDAR TERRAIN MAPPING IN FORESTED AREAS

The application of LIDAR for mapping of forested terrain has been a prominent research theme in recent years. The main challenge in using LIDAR to develop terrain models lies in the development of filtering algorithms that effectively separate the LIDAR returns reflecting from the ground surface from those reflecting from the vegetation. These algorithms typically employ an iterative approach where "spikes" in the last return LIDAR data set are systematically removed based upon a measure of local curvature (Sithole and Vosselman 2003). While several of these algorithms are documented in the open literature, for the most part the development of these techniques has remained a proprietary activity (Elmqvist 2002, Haugerud and Harding 2001, Kraus and Pfeifer 1998). In several studies, the accuracy of digital terrain models derived from LIDAR was found to be significantly higher than that obtained from conventional aerial photogrammetric methods. For example, in several studies conducted in a Pacific Northwest conifer forest in western Washington State (USA) that evaluated the accuracy of LIDAR-derived and USGS DTMs through comparison to surveyed check point elevations, the root mean square error (RMSE) of the LIDAR DTM was found to be 0.32 meter, while the RMSE of the standard USGS 10-meter DTM was 8.8 meters (Andersen et al. 2005b, Reutebuch et al. 2003). Visual assessment of these DTMs in this forested area confirms the quantitative findings – the high level of detail contained in the LIDAR DTM, including small-scale drainage features, road prisms, and microtopography, is quite evident when compared to the coarser resolution of the USGS 10-meter DTM (Figures 3-3 and 3-4) (Plates 3-3 and 3-4). The accuracy of the LIDAR-derived DTM generated from high-density LIDAR data (e.g. 4 returns/m^2) was not found to be highly correlated with any measure of canopy density, indicating that LIDAR can be effectively used to generate highly accurate DTMs even in areas with very dense forest cover (Reutebuch et al. 2003).

5. LIDAR FOR FOREST INVENTORY APPLICATIONS

Methodologies for extracting forest measurement information from LIDAR data have been carried out at two different scales - individual tree-level and plot-level - depending upon the type of data used and the type of application. When data are acquired at a high enough density (resolution), the dimensions of individual trees composing the overstory canopy can be measured using the LIDAR-derived canopy surface model (Figure 3-5) (Plate 3-1). In one approach, computer vision algorithms are implemented to automatically recognize and measure various attributes of individual trees, including total height, crown height and crown diameter.

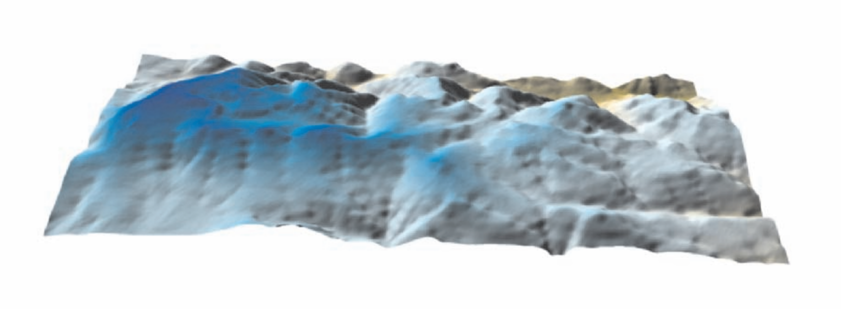

Figure 3-3. Shaded relief of the USGS 10-meter DTM for Capitol Forest study area, Washington, USA. (See also color plate 3-3 on p. CP2)

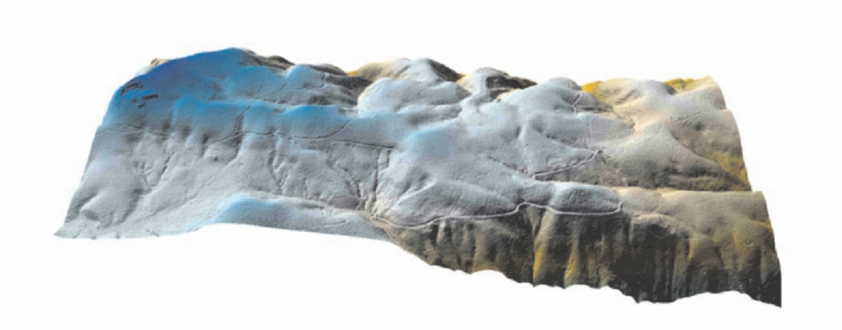

Figure 3-4. Shaded relief of the LIDAR-derived digital terrain model for Capitol Forest study area, Washington, USA. (See also color plate 3-4 on p. CP3)

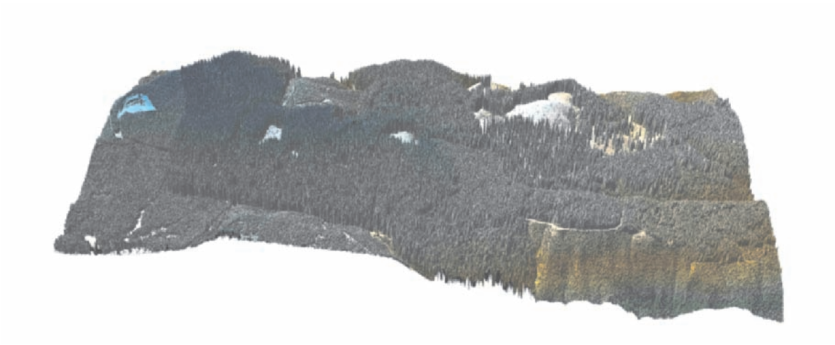

Figure 3-5. Shaded relief of the LIDAR-derived canopy surface model for Capitol Forest study area, Washington, USA. (See also color plate 3-5 on p. CP3)

Probably the most widely used computer vision algorithm for extraction of individual tree-level information from high density LIDAR is the morphological watershed algorithm (Soille 1999). In this algorithm, the (inverted) canopy surface model is considered to be a collection of small "watersheds" associated with the inverted shapes of individual tree crowns. The morphological watershed algorithm then segments the canopy height model into areas associated with each tree crown composing the surface (Figures 3-6a and 3-6b) (Plates 3-6 and 3-7). Several studies have shown that morphological computer vision techniques (such as the watershed algorithm) can be effectively used to identify tree crown structures and measure individual tree attributes (Persson et al. 2002, Schardt et al. 2002, Straub 2003, Ziegler et al. 2000). When LIDAR data from different years are acquired, this approach can be used to analyze height growth and crown expansion at the individual-tree level (Andersen et al. 2005c, Yu et al. 2004).

An alternative approach to the analysis of LIDAR for extraction of forest measurements uses regression to model the relationship between a collection of metrics describing the spatial distribution of LIDAR returns within a plot area (e.g. 0.1 ha) and stand measures derived from field measurements collected at this plot (e.g. basal area, stem volume, dominant height). This approach is particularly useful when LIDAR data are collected at a lower density, or the vertical structure of the forest is complex (i.e. composed of multiple canopy strata). Typically, the metrics used to describe the spatial distribution of LIDAR returns in a plot area include several height quantile measures (e.g. 10th, 25th, 50th, 75th, and 90th percentile heights), as well as other metrics such as the mean height, maximum height, and coefficient of variation of height, and a LIDAR-derived measure of canopy cover, e.g. the percentage of LIDAR first returns that reflect from the canopy (e.g. higher than 2 meters above the terrain). This plot-level approach has been used by researchers in the United States and Europe to estimate stand inventory parameters in several different forest types, where predictive regression models were shown to explain from 80 to 99 percent of the variation (i.e. R^2) in field-measured values (Means et al. 2000, Næsset 2002, Næsset and Okland 2002). In a study carried out using 99 field plots measured at the Capitol Forest study area in Washington State (described previously), strong regression relationships between LIDAR-derived predictors and field-measured values were found for several critical inventory parameters, including basal area ($R^2 = 0.91$), stem volume ($R^2 = 0.92$), dominant height ($R^2 = 0.96$), and biomass ($R^2 = 0.91$) (Figures 3-7a, 3-7b, -37c and 3-7d) (Andersen et al. 2005c). This approach has also been used to estimate several important canopy fuel parameters using LIDAR data (Andersen et al. 2005a). Although the results are somewhat preliminary, recent research has also indicated that the intensity of the near-infrared reflection from LIDAR data acquired in leaf-off conditions can be used to determine species type (Brandtberg et al. 2003).

6. PRINCIPLES OF INTERFEROMETRIC SYNTHETIC APERTURE RADAR

Side-looking airborne RADAR (SLAR) is an active imaging technology that operates in the microwave portion of the electromagnetic spectrum[2]. SLAR operates on the principle of emitting short pulses of microwave energy and recording the reflection from a given area on the ground. The resolution of a side-looking RADAR imaging system in the cross-track direction (i.e. perpendicular to the flight path) is determined by the pulse duration (shorter pulse = higher across-track resolution), while the resolution of the RADAR in the azimuth direction (parallel to flight direction) is determined by the length of the antenna aperture (i.e. longer aperture = higher azimuth resolution) (Figure 3-8).

Because practical considerations will limit the length of a real aperture, in synthetic aperture RADAR (SAR) imaging a very long aperture is synthesized through integration of the magnitude and phase information of the returned echoes from a feature over the entire time it is in view of the RADAR (Waring et al. 1995). Because relatively long-wavelength RADAR energy penetrates through (even dense) water vapor, RADAR imaging is often possible in situations where optical sensing is severely limited or even impossible due to persistent cloud cover. The strength of the signal received by RADAR antenna for a given ground resolution cell (represented by *RADAR backscatter coefficient* σ^o) is mainly a function of the wavelength of the microwave energy, the characteristics of the imaged feature, and the geometry of the image acquisition (Jensen, 2000).

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[2] Imaging RADAR systems are operated from both airborne and spaceborne platforms. Spaceborne systems typically have spatial resolutions ranging from 10 - 30 m, while airborne RADAR systems have resolutions from 1-10 meters.

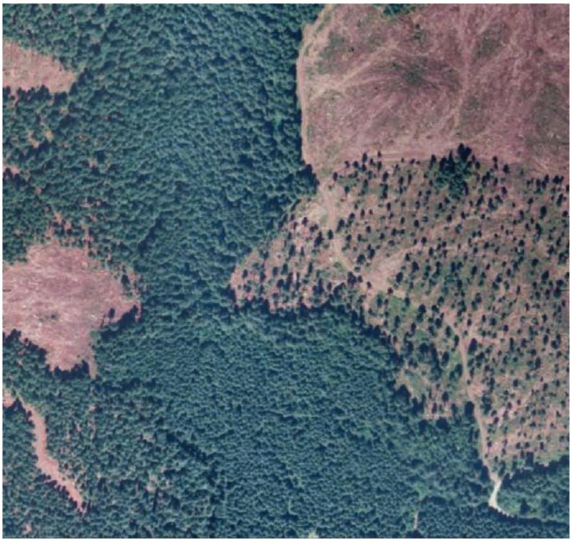

Figure 3-6a. Orthophoto of selected area, Capitol Forest study area, Washington, USA. (See also color plate 3-6a on p. CP4)

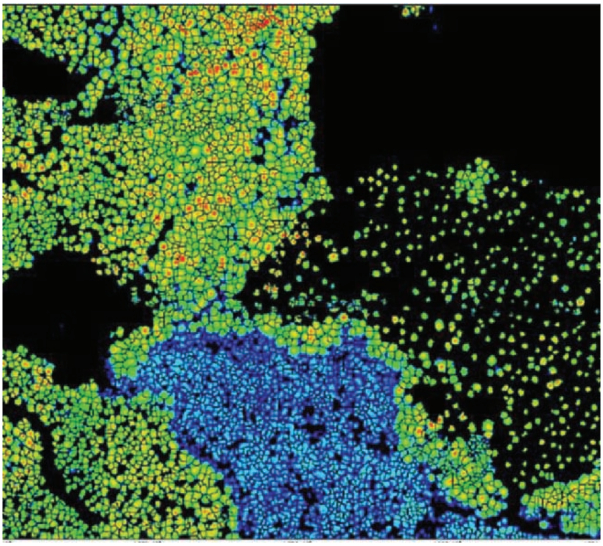

Figure 3-6b. Individual tree-level segmentation of LIDAR canopy height model via morphological watershed algorithm (color-coded by height: blue = 20 m, green = 30 m, yellow = 40 m, red = 50 m; black lines indicate boundaries of segments; black areas indicate areas with no tree cover). (See also color plate 3-6b on p. CP4)

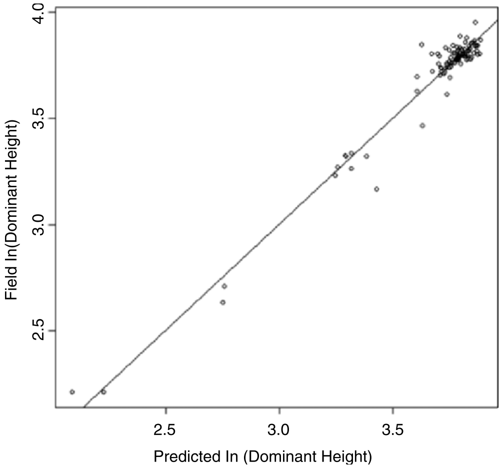

Figure 3-7a. Results of plot-level LIDAR-based estimation of forest inventory parameters at Capitol Forest study site. Scatterplot represents relationship between predicted (x) and field-based (y) estimates of dominant height at the individual plots. Line represents 1:1 relationship.

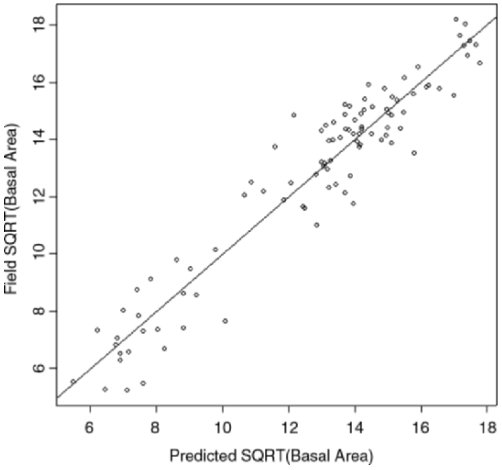

Figure 3-7b. Scatterplot representing relationship between predicted (x) and field-based (y) estimates of basal area at the individual plots.

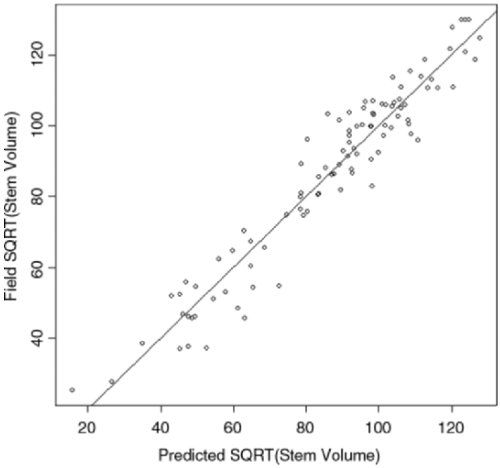

Figure 3-7c. Scatterplot representing relationship between predicted (x) and field-based (y) estimates of stem volume at the individual plots.

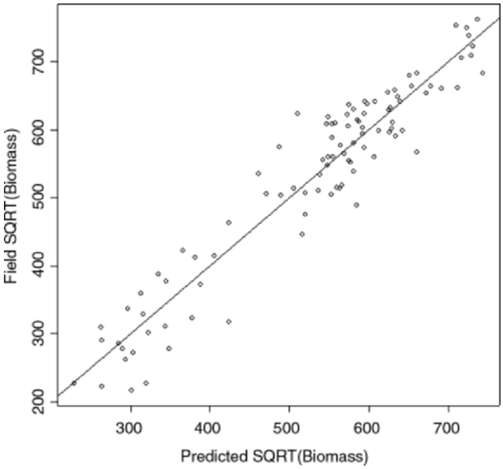

Figure 3-7d. Scatterplot representing relationship between predicted (x) and field-based (y) estimates of biomass at the individual plots.

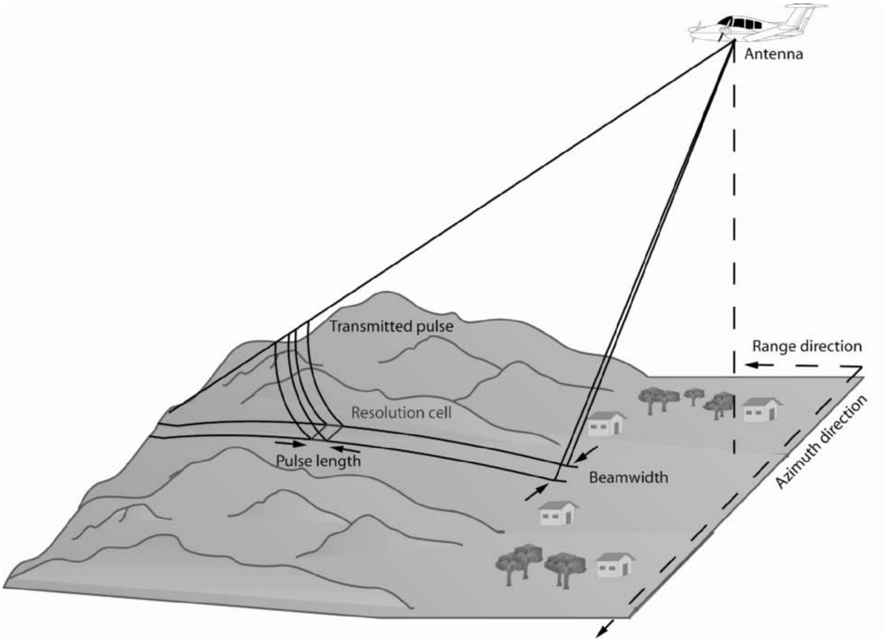

Figure 3-8. Geometry of a side-looking airborne RADAR system. Adapted from Lillesand and Kiefer (1987).

In the context of forest vegetation mapping, the wavelength of the RADAR system will determine whether the SAR backscatter is dominated by surface scattering or volume scattering. When relatively short-wavelength (i.e. 3 cm for X-band) microwave energy interacts with the surface of the forest canopy, the energy is scattered by small-scale components of the canopy, such as the foliage and small branches. Therefore at these wavelengths the RADAR energy reflects mainly from the surface of the canopy (Figure 3-9). In contrast, RADAR energy with relatively long wavelengths (i.e. 74 cm for P-band) will penetrate into the canopy and reflect from large scale components composing the canopy, including large branches, stems, and the terrain surface. Therefore for long wavelength RADAR systems the reflectance is dominated by volume scattering from large-scale canopy features and surface scattering from the terrain surface (Figure 3-9). The magnitude of RADAR backscatter (i.e. reflection) from a feature is also dependent upon a variety of surface characteristics, including structure, surface roughness, and water content. In addition, some SAR systems have the capability to send and receive energy with different polarizations. Because RADAR energy can be depolarized upon interaction with various surface features, independently recording the reflection of like-polarized energy (e.g. vertical send – vertical receive (VV) or horizontal send – horizontal receive (HH)) and cross-polarized energy (e.g. vertical send – horizontal receive (VH) or horizontal send – vertical receive (HV)) can yield valuable information regarding the characteristics of imaged features, and can be particularly useful in the analysis of vegetation type and structure. For example, if the RADAR energy interacts mainly with single scatterers at the surface of the canopy, the energy is not depolarized and there is a strong reflection of like-polarized energy. In contrast, if the RADAR energy is reflected from multiple scatterers within the canopy structure, it is often depolarized and there is a strong reflection of cross-polarized energy (Jensen 2000). A RADAR image acquired from a system with a particular frequency, polarization, and incidence angle can therefore provide information related to canopy water content, vegetation type, biomass components (foliage, branches, stems), and canopy structure (leaf orientation, leaf area index, main stem geometry and spatial distribution) (Jensen 2000, Carver 1988).

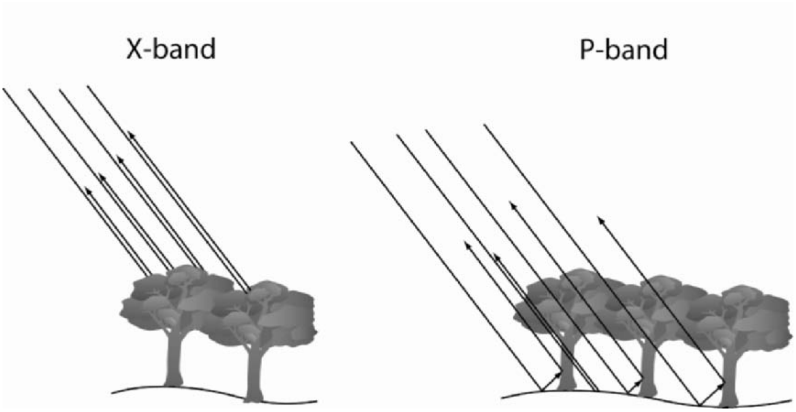

Figure 3-9. Short wavelength X-band RADAR energy reflects from canopy surface while long wavelength P-band energy penetrates through canopy and reflects from stems and terrain surface Adapted from Moreira et al. (2001).

While SAR images can provide important information relating to vegetation properties, the inherently 2D format of the data only allows for indirect estimation of 3D structural attributes within a forested scene. The development IFSAR in recent years has enabled the direct measurement of the elevation of scattering elements within a ground resolution cell. Determining the 3D coordinates of reflecting surfaces using IFSAR involves quantitative analysis of the phase shift between two complex-valued RADAR images obtained with slightly different imaging geometries. The interferometric phase difference at each image point is related to the difference in path length between each antenna and the point, which is a function of surface elevation. This interferometric phase information can be combined with knowledge of the sensing geometry for each antenna to obtain an elevation for each image point (Rosen et al. 2000) (Figure 3-10). Because the penetration of microwave energy into a forest canopy is a function of RADAR wavelength, the interferometric surface elevation obtained in a forested setting will also be a function of wavelength. For example, the interferometric measurements obtained from an X-band RADAR with a relatively short wavelength will represent the "first-return" surface of the canopy (Figure 3-11) (Plate 3-11), while the interferometric elevation measurements from a long-wavelength P-band system will generate a surface corresponding to the underlying terrain and understory vegetation (Figure 3-12) (Plate 3-12).

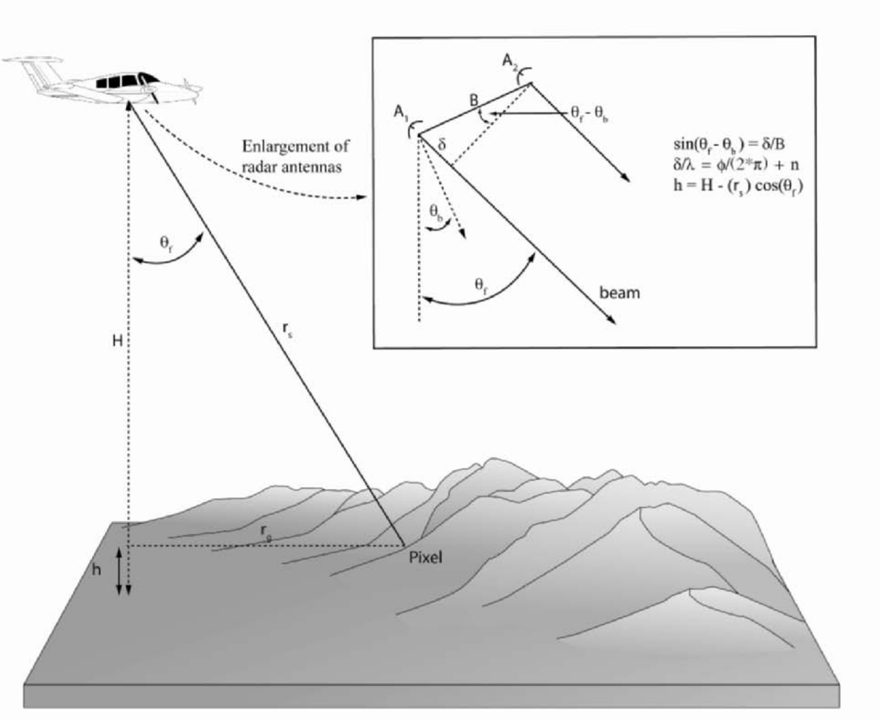

Figure 3-10. Geometry of RADAR interferometry. Adapted from Mercer (2004).

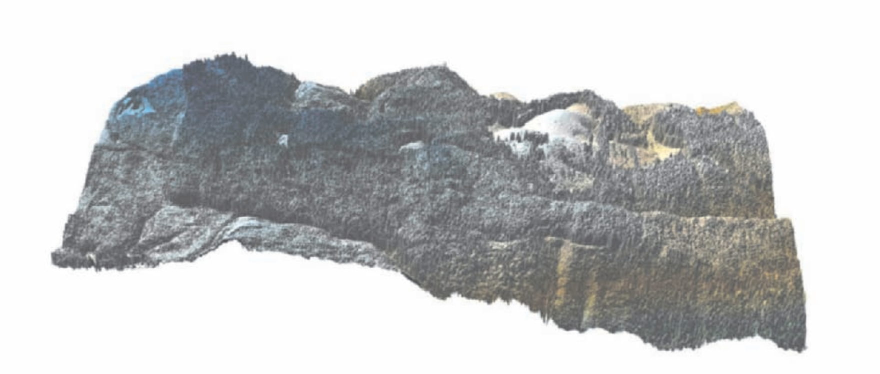

Figure 3-11. Shaded relief of the canopy surface model generated from X-band IFSAR data at Capitol Forest study area, Washington, USA. (See also color plate 3-11 on p. CP5)

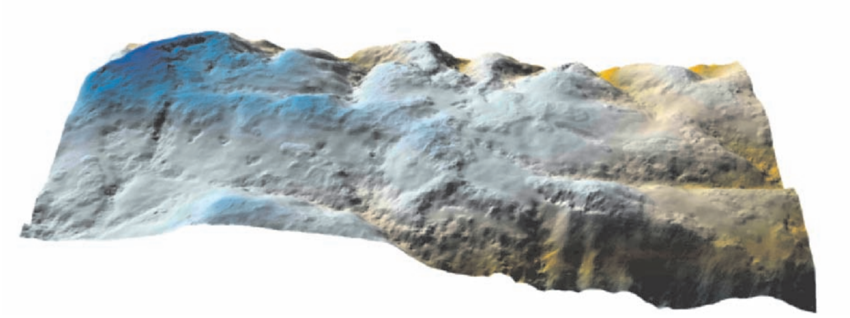

Figure 3-12. Shaded relief of the digital terrain model generated from P-band IFSAR data at Capitol Forest study area, Washington, USA. (See also color plate 3-12 on p. CP5)

7. IFSAR TERRAIN MAPPING IN FORESTED AREAS

Several very-large scale mapping campaigns in recent years have established the cost-effectiveness of the IFSAR technology for terrain mapping. For example, the commercial vendor Intermap Technologies Corporation has embarked on an ambitious campaign to acquire topographic data at national scales using their Star-3i X-band IFSAR system. Intermap has already acquired IFSAR-derived topographic data for all of Great Britain, through the NextMap Britain program. Because the accuracy of interferometric measurement is also a function of wavelength, in areas within little vegetation the X-band IFSAR-derived surface can be highly accurate. For example, in a study carried out in Germany, the accuracy of an X-band IFSAR-derived DTM was reported at 20 cm (Schwäbisch and Moreira 1999). Validation of the topographic data acquired in the NextMap Britain project also reflects this level of accuracy. An accuracy assessment of the NextMap Britain project, carried out via comparison to LIDAR, GPS, and photogrammetric checkpoints, resulted in RMSE values ranging from 0.5-1.1 m in various conditions (Mercer 2004). While the topographic data acquired from X-band IFSAR systems are quite accurate in areas with little or no vegetation cover, the accuracy of these data declines in areas with dense forest cover, due to the fact that it is essentially a "first return" surface. For example, Hodgson and others (2003) evaluated the accuracy of X-band IFSAR-derived DTMs in a mixed deciduous forest in North Carolina and reported an overall RMSE of 10.7 meters.

The inherent limitations of X-band systems for topographic mapping in forested areas has led to increased interest in the development and application of airborne IFSAR systems that utilize RADAR energy at longer wavelengths (i.e. P-band) that will penetrate through the forest canopy and reflect from the underlying terrain surface. For example, a recent study reported an RMSE of 2.6 meters for a P-band IFSAR-derived DTM acquired for a conifer forest with varying levels of forest density in the Pacific Northwest (via comparison to 347 high-accuracy topographic check points acquired with a total station survey) (Andersen et al. 2005b). An earlier study of P-band accuracy carried out in a forested area of Germany showed an accuracy of 5 meters (Hofmann et al. 1999). While these recent results have indicated the potential of P-band IFSAR for topographic mapping over large areas, to date the application of these systems has been limited to the research domain, mainly due to constraints upon the available bandwidth and interference with communication systems.

8. MULTI-FREQUENCY IFSAR FOR FOREST INVENTORY APPLICATIONS

The use of multi-frequency IFSAR data allows for independent measurement of both the canopy and terrain surfaces, where canopy level measurements are generated from X-band and terrain-level information is obtained from the P-band IFSAR data (Figure 3-13) (Plate 3-13). An IFSAR-derived canopy height model can be generated easily as the difference between the X-band canopy surface model and the P-band terrain model.

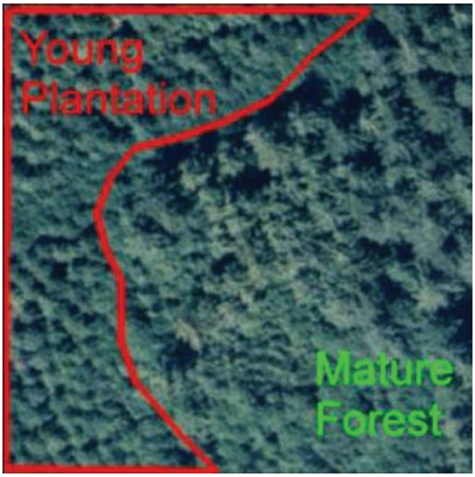

Figure 3-13a. Orthophoto of area with young plantation and mature forest in Capitol Forest study area, Washington, USA. (See also color plate 3-13a on p. CP6)

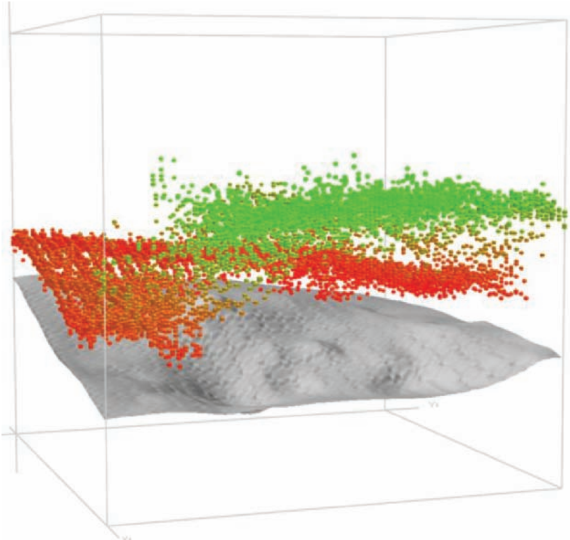

Figure 3-13b. 3D graphical visualization of above area showing X-band IFSAR elevation measurements (color-coded by height) overlaid on P-band digital terrain model. (See also color plate 3-13b on p. CP6)

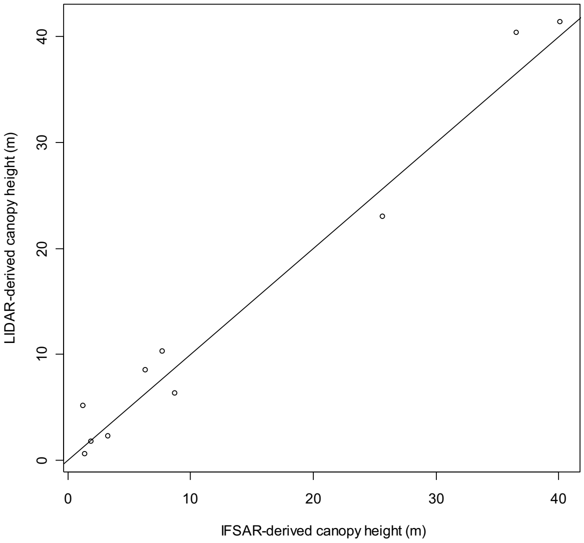

Figure 3-14. Relationship between LIDAR-derived stand heights and IFSAR-derived stand heights. Stand height is calculated as the median value of the canopy height model within a stand. Line represents 1:1 relationship.

In a study carried out at a conifer forest within the Pacific Northwest, using a multi-frequency X-band/P-band system, a high correlation was found between the IFSAR-derived canopy height and LIDAR-derived canopy height at the stand level (r = 0.99) (Figure 3-14). The geometric (height) information provided by SAR interferometry has the potential to dramatically increase the utility of RADAR data for forest inventory applications. Because even long-wavelength P-band RADAR backscatter tends to be less and less sensitive to changing biomass levels beyond 100 tons per hectare due to saturation, the utility of SAR for forest inventory in highly productive temperate forests and tropical rainforests can be limited (Imhoff 1995). Recent studies have shown that interferometric observables, such as coherence and phase, are more sensitive than RADAR backscatter to changes in forest structure parameters at higher biomass levels (Treuhaft and Siqueira 2004). The use of IFSAR therefore reduces the effect of RADAR saturation and provides for more accurate estimation of forest inventory variables across a broad range of forest types. In a study investigating the utility of X-band/P-band IFSAR data for tropical forest mapping in a region of the Brazilian Amazon with biomass levels reaching 350 tons/ha, high correlations were reported between interferometric height (X-band – P-band)

and forest height from ground measurements ($R^2 = 0.87$) (Santos et al. 2004). In the same study, a predictive linear model for biomass was developed using P-band backscatter (HH polarization) and interferometric height as independent variables ($R^2 = 0.89$). Therefore, the results of this study indicate that the inclusion of interferometric variables can successfully alleviate the problem of RADAR saturation in tropical forest biomass estimation. It should be mentioned that recent theoretical developments in the electrical engineering community have indicated the potential for incorporating the polarimetric information into the interferometric analysis of forest structure and terrain (Cloude et al. 2002). Recent research has also proposed using IFSAR data acquired at multiple baselines in order to infer the vertical distribution of canopy materials (Reigber et al. 2000).

9. CONCLUSIONS

The quality and quantity of spatial information now becoming available to the resource management community due to the emergence of high-resolution active remote sensing technologies is truly remarkable. In the near future, a forest manager can expect to have accurate, and highly-detailed, digital information relating to terrain morphology and forest stand structure provided as standard remote sensing deliverables. Although the concurrent development of high-resolution passive remote sensing technologies, including hyperspectral airborne sensors such as the Compact Airborne Spectrometer Instrument (CASI), also promises to provide a tremendous amount of information relating to species class and condition, it can be argued that the emergence of active airborne remote sensing technologies, such as LIDAR and IFSAR, will represent a truly revolutionary advance in how we measure and inventory natural resources. The demonstrated capability of these systems to provide a direct measurement of 3D structure and terrain, enabled through the application of precise geopositioning technologies such as GPS and inertial measurement systems, will allow foresters to implement a site-specific approach to environment management, optimizing use and therefore increasing the value of the forest resource.

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Chapter 4

FOREST INFORMATION SYSTEMS

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Abstract: This chapter considers some general aspects of forest information systems. The nature of information is discussed. A forest information system will comprise at least the components input, analysis, estimation and prediction, decision support, presentation, and visualization. With respect to information needs, a typology of information systems is presented. Information systems utilize the entire spectrum of computer sciences and computer technology. Methodological concepts are presented in the context of the different categories of information systems.

Keywords: Forest information systems; GIS; metadata; methodological components.

1. INTRODUCTION

"Knowledge is power," wrote the philosopher and science theoretician Francis Bacon in 1597. In the naval battle of Lepanto, Spain and Venice had just ended the long-lasting dominance of the Osmanian Empire in the Mediterranean Sea by using novel ships and light canons. Spanish, Portuguese, and English ships were sailing to remotest continents, guided by increasingly accurate navigation instruments and telescopes. Belief in the unlimited potential of knowledge had created a European-wide spirit of optimism. Francis Bacon and his contemporaries were deeply convinced that one day knowledge would solve all problems of humanity.

Today, knowledge management has become a major concern for society. Both the volume and variety of available information poses a challenge: amid the seeming avalanche of information available on any particular topic, which is the vital information? Decision makers need to know what they

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know and be able to find purposeful information distilled to a degree that facilitates effective and objective decisions. Today the complexity and interconnectedness of various areas of human societies on local, regional and global scales renders an adaptation of Bacon's theorem necessary: only shared knowledge is power.

Improving access to forest information and the use of digital information systems were formally recognized as a priority by the United Nations Conference on Environment and Development within Agenda 21, Chapter 40 (UNCED 1992). Implementation of Agenda 21, facilitating intergovernmental negotiations and monitoring conventions and efforts towards sustainable development, should be supported by electronic means. To ensure effective and equitable availability of information, existing national and international mechanisms for information processing and exchange should be strengthened. In 1997, the Intergovernmental Panel on Forests re-emphasised the importance of improving access to forestry information (CSD 1997).

2. THE NATURE OF INFORMATION

The base of any information system is data. Data are the recorded values of attributes of objects. They can be raw measurements and assessments according to measurement rules or definitions, or be derived by functions or models. From the perspective of information technology, data are a structured sequence of symbols that follow certain rules (Stahlknecht and Hasenkamp 2004).

Data, as such, do not constitute information in and of themselves; they are often not of much value to decision making until they have been transformed or converted into something more meaningful and useful in terms of information needs. Semantics are used to ascribe meaning to data, thereby transforming data into information. The user needs to know the 'correct' rules for interpretation in order to extract information from data. Depending on the vertical level of decision processes, data need to be aggregated and condensed (Eisenführ and Weber 2004). In information theory, which is concerned with techniques and methods of data processing and telecommunication, information is understood as a technical measure that is associated to data according to probabilities (Yoshida 2001). However, forest information systems are generally using the concept mentioned earlier, but implement models based on probabilistic assumptions, where sustainable forest management has to consider the future development of forests with respect to management regimes and natural risks (Pretzsch 2001).

In a philosophical sense, knowledge is the substantiated and rational recognition in contrast to opinion, conjecture or belief (Kant 1787). Knowledge can be gained by firsthand experience through accidental observations, systematic investigations, or deductions, or it can be acquired by learning. Knowledge has two dimensions: a conceptual, strategic (big-picture) dimension and a detailed or tactical dimension (McCloy 1995). For example, forest ecology and forest growth and yield research provide the conceptual understanding of conditions and processes driving the development of forests over time, while forest resource managers need details that allow for the construction of an adequate technical knowledge base on which they can make the relevant decisions for the sustainable management of forest.

Information and knowledge are only as good and reliable as the underlying data, from which they are derived. It is in the nature of things that once data are stored in a computer they are regarded as a true reflection of reality. Data are always subject to various sources of errors (Groves 1989, Gertner and Köhl 1992), which have to be carefully monitored and can be quantified by accuracy, which refers to the size of deviations from a 'true' value (Cochran 1977). In the context of forest resources, spatial, thematic and temporal accuracy of data all need to be considered.

3. THE NATURE OF FOREST INFORMATION SYSTEMS

Forest information systems (FIS) should provide a comprehensive set of information to the decision maker, support the implementation of more timely decisions, and improve the quality of decisions (Dykstra 1997). Because many decisions have a spatial context, geographic information systems (GIS) have become a widely used component of FIS to facilitate handling of spatial data (McCloy 1995). A FIS is a management tool rather than a playground for computer enthusiasts. Therefore it is essential that the system interface to the user is easy to learn, use, and understand. The current trend toward use of computer graphic interfaces has improved the convenience by simultaneously requiring minimum training. A FIS is often based on sophisticated technology and implemented by experts with sophisticated technological skills. However, a user has generally minor interest in technical solutions, but demands a system that is efficient, easy to use, flexible, and reliable.

FIS have different components (McCloy 1995, Gunter 1998):

- An input interface allowing for editing, updating, modifying, and deleting data

- A database
- One or more analytical engines providing tools for statistical and/or numerical analyses of available data sets
- Tools for estimation and prediction to forecast future developments
- A decision-support system
- Tools for presentation and visualization

Not all components listed above have to be included in operational FIS. For example, IUFRO's Global Forest Information System (GFIS)[3] provides access to literature, with no analysis, estimation, and decision support. The European Forest Information System (EFIS)[4] was developed to compile, process, analyze and disseminate available forestry information of various heterogeneous data sources on international, national and regional levels. It includes analytical engines to process available information according to user's requests, but does not provide tools for predicting future developments. The European Forest Fire Information System (EFFIS)[5] is focused both on the development of systems to provide forest fire risk forecast based on existing fire risk indices, and on the development of new integrated forest fire risk indicators. The prediction tools is a central component of the system, which allows to generate forest fire risk forecast maps of Europe processing 0-24 hours and 48-72 hours weather forecast data. Several German forest administrations joined efforts to develop a common forest information system (FOGIS)[6] that enables local managers with minor computer skills to process forest related (spatial) data and support sustainable forest management. The system contains modules for data import, user administration, processing of data, and preparation of mapped output and combines a database for non-spatial data and a GIS for spatial data. It is designed for applications intended for use e.g. in forest management planning, site mapping, mapping of forest biotopes and forest functions, or forest road information.

FIS involve technologies such as computer science, remote sensing, GIS, image processing, modeling and simulation, and internet and communication protocols. Depending on the technical realization of the system, data utilized are either stored in a central database or are retrieved from distributed databases. Merging data from various sources and sectors is not straightforward because different spatial, temporal, and thematic resolution as well as data formats render harmonization necessary. Metadata standards

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[3] http://www.gfis.net

[4] http://www.ec-gis.org/efis

[5] http://inforest.jrc.it/effis/

[6] http://www.intend.de/pages/ger/proj/proj_mn.htm

such as the Dublin Core Metadata Initiative (DCMI)[7] offer a possibility to integrate multiple disparate data sources. For situations in which data sources are to be assessed via the internet, additional tools for information retrieval and resource allocation are required. Figure 4-1 presents the dimensions of a FIS.

Decision support provides the interface with the decision maker. Here the information retrieval capacities of the system and the information needs of the user must be brought together. The method of information use affects the form in which the information is presented, e.g. as statistics, digital data, graphs or maps. It is advisable to supplement any output of the system by information on its reliability.

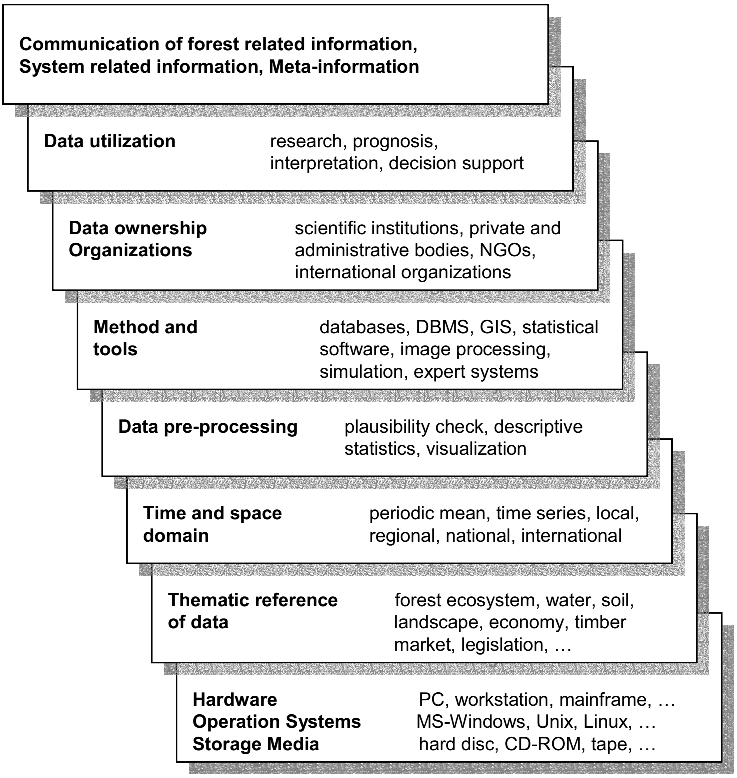

Figure 4-1. Dimensions of forest information systems.

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[7] http://dublincore.org

Forest information systems recognize three types of information needs (FAO/ECE/ILO, 1992):

- information for strategic planning and analysis,
- information for tactical (medium and short-term) planning, and
- information for operational management and control.

As information needs vary for different tasks and responsibilities in an organisation information systems need to map information flows through institutions and the different levels and responsibilities for decisions.

There are costs associated with information management. Data on phenomena have to be measured, the data have to be analyzed in order to extract information, decision processes have to operate on the information, and the decisions have to be translated into actions. Costs originate from assessments, analyses, and decisions. A utility function can be used to contrast the various costs and benefits (Figure 4-2).

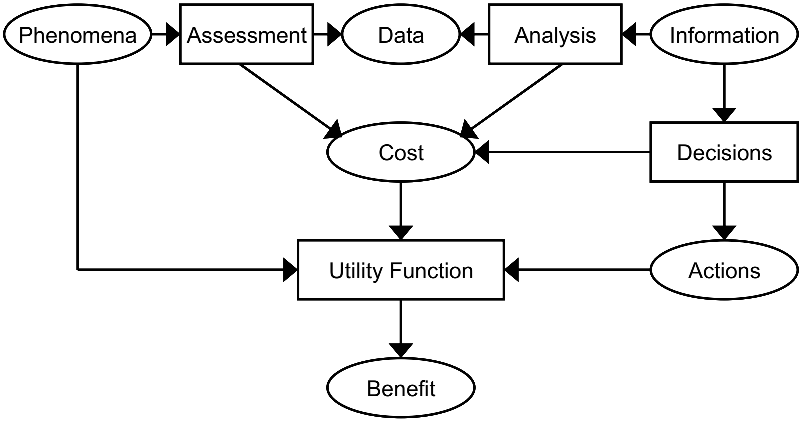


Figure 4-2. Costs and benefits of forest information systems.

Implementation of a FIS does not lead to a benefit per se. In order to optimize the utility function, it is advisable to customize a FIS to the specific purposes and conditions. However, considerable savings can be realized by modular designs that assemble tried and tested components, that and reduce the development of new components to a minimum (Gunther 1998).

4. A TYPOLOGY OF FOREST INFORMATION SYSTEMS

Information systems can be assigned to one of the following categories. The classification criterion is the level of analysis achieved with information. Table 1 presents different classes of information systems (columns) and links them with the different methodological components utilized (rows).

Table 4-1. Methodological components within classes of information systems (after Page and Hilty, 1995).[a]

	Monitoring and control systems	Regular information systems	Evaluation and analysis systems	Decision-support systems	Integrated information systems
Database systems & GIS	✓	✓✓	✓✓	✓	✓✓
Modelling & simulation	✓	👎	✓✓	✓✓	✓
Knowledge-based systems	✓✓	👎	✓	✓✓	✓
Computer graphics & visualization	✓✓	✓	✓✓	✓	✓
User interfaces & software ergonomics	✓✓	✓✓	✓	✓✓	✓✓
Artificial neural network & fuzzy logic	✓	👎	✓✓	👎	✓
Integration	✓✓	✓✓	✓	✓	✓✓

[a] ✓✓ = of particular relevance ✓ = relevant, 👎 = not relevant

4.1 Monitoring and control systems

These systems can be assigned to the classical tasks of measuring, controlling, and regulating. They are used for either environmental monitoring (pollution of air, water, soil or vegetation as well as noise and radiation), or control of technical processes within the scope of computer-assisted process control.

4.2 Conventional information systems

This class groups systems concerned with the storage, analysis, organization, integration, and presentation of different data sources and data formats, such as

- measurements from monitoring systems,
- formatted data such as areas, timber volumes, growth figures, mortality, or potential cut, and
- unformatted documents such as laws and regulations, or relevant literature.

Specific requirements in relation to time and space often need to be considered. Concerning the contents of available information, little more than a targeted analysis and compilation of data can be achieved. The use of modeling techniques is limited and rarely extends beyond the application of functional relationships such as volume or biomass equations.

4.3 Evaluation and analysis systems

Evaluation and analysis systems allow for the processing of data by means of complex mathematical and statistical methods and models. Dispersal and prognostic models, image analysis methods and simulations are associated with this class. Results of analyses are information about the potential impact of alternative management plans. Examples of evaluation and analysis systems are the prognosis of potential timber supply under different silvicultural treatments, or the prognosis of changes of habitat suitability by introducing new landscape management regimes.

4.4 Decision-support systems

Decision-support systems offer a decision maker direct support during the decision process by providing assistance with the evaluation of alternatives or substantiating decisions. In contrast to evaluation and analysis systems, decision-support systems include explicit valuation and rating methods. In addition, inference methods are typically used; here, especially, knowledge-based systems originating from the domain of artificial intelligence are often needed.

4.5 Integrated information systems

Information systems are not only implemented in the forestry sector, but are widely used in all environmental fields. This includes both different thematic alignments as well as different hierarchical levels (e.g. enterprises, communities, federal states, or international organizations). Many of the systems implemented cannot be assigned to one of the specific categories mentioned above, as they combine different components. Such systems are called integrated information systems. It is to be expected that these systems will gain importance in the future, and will be implemented as distributed systems. The integration of different concepts from information technology, data formats and system classes (e.g. simulation systems, knowledge-based systems) is a particular challenge for applied computer sciences.

5. METHODOLOGICAL COMPONENTS OF INFORMATION SYSTEMS

When developing and implementing information systems, the entire spectrum of computer science and technology comes into play. However, some concepts and methods are more relevant than others. Table 1 compares the methodological components within classes of information systems. Database and GIS, computer graphics and visualization, user interfaces and software ergonomics as well as integration are relevant for all information system categories.

5.1 Database systems and geographic information systems

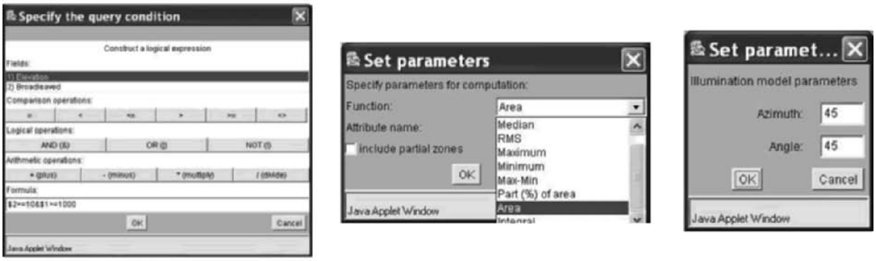
Databases are undoubtedly critical components of information systems. Due to their spatial context, many forest information systems can be considered to be extensions of GIS that contain, in addition to geo-referenced data and relevant methods, additional thematic and non-formatted data with a temporal relation (Bettinger and Wing 2003). Specific problems arise when the complex, structured objects of the forest and environmental sectors need to be implemented in data models of conventional database systems. Another challenge is the integration of possibly numerous heterogeneous data sources into distributed systems, which are a prerequisite for genuine exhaustive information systems for strategic management. Orientation and user guidance within extensive information systems with numerous heterogeneous databases requires the creation of metadatabases.

5.2 Knowledge-based systems

Increasingly, attempts are undertaken to utilize knowledge-based systems, especially expert systems, for information management (Schmoldt and Rauscher 1996). The increasing number of projects in the environmental context cannot belie that the proportion of systems applied in everyday business is relatively small. Within the environmental sector most of the expert system developments are in the category of diagnosis and interpretation. Promising fields of application are knowledge-based support for utilization of databases, processing of information requests, and monitoring tasks, as well as training and education.

5.3 Modeling and simulation

Modeling and simulation methods have a long tradition in the forestry sector, and their practical application is well established. Modeling and simulation are essential for the analysis of complex, dynamic systems, because they are typical for the forestry and environmental sectors. Continuing addition of modeling and simulation components will increase the number of problems that can be treated by information systems. While simulation and modeling techniques were up to now to a large degree developed as stand-alone systems, demand for their integration into information systems will almost certainly increase in the near future.



Formula: $2>=10&$1>=1000

Function: Area

Azimuth: 45

Angle: 45

Figure 4-3. Example of a user interface (from EFIS).

5.4 User interfaces and software ergonomics

A prerequisite for the wide application of forest information systems is the assignment of modern, mainly graphical, concepts for the design of user interfaces. From experience, especially within the group of “occasional users,” the supply level can be multiplied by offering user-friendly interfaces. Natural, non-task-specific languages should be requisite for queries. Figure 4-3 presents an example of user interfaces from the EFIS. The right box guides a user through the data query and offers tools for various selection criteria and embedded analyses. Parameters for computations can be specified in the next window, while the window on the right gives an example for setting options for the presentation of results in maps (Kennedy et al. 2003).

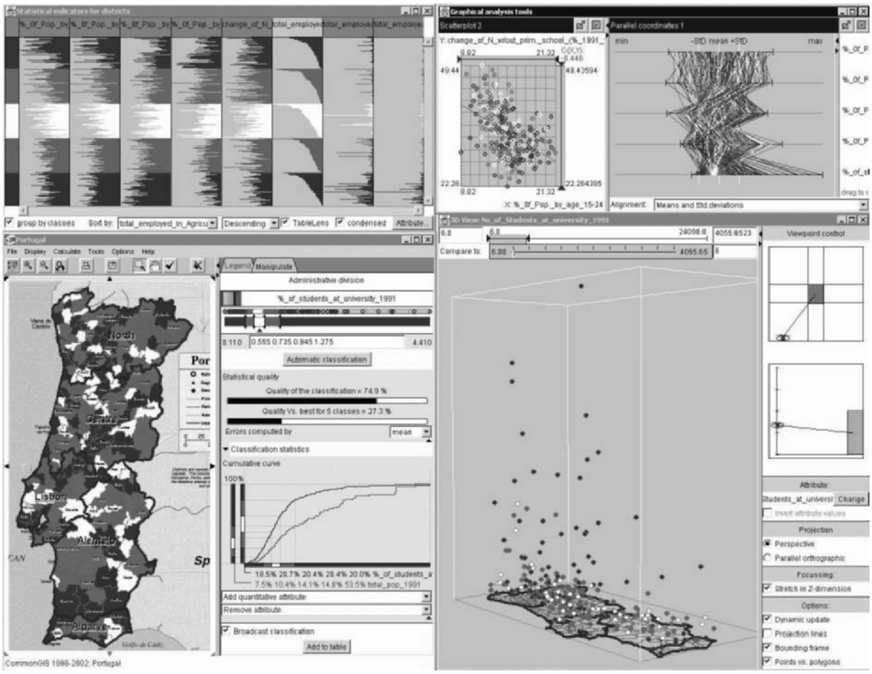
5.5 Computer graphics and visualization

Use of computer graphics as an instrument for sophisticated visualization is of vital importance in almost any decision process. Data visualization is an essential component of exploratory data analyses because the human eye is so adept at detecting complex relationships. Many tasks in forest ecosystem management require the comparison and integration of numerous parameters referring to different geometric and geographic objects or different time scales. Computer graphics and visualization facilitate data evaluation and decision processes by presenting complex problems in an intuitively clear way.

Recently, influenced by ideas of scientific visualization and exploratory data analysis, more attention has been given to the role of the map as a tool to support visual thinking and decision making (MacEachren 1994a and 1994b, MacEachren and Kraak 1997, Kraak 1998). To play this role effectively, a map needs two principal additions: interaction and dynamics. The EFIS (Kennedy et al. 2003) provides a Visualization Toolkit that allows the use of various dynamic presentation methods, while also encompassing options for paper-based and computer-based static mapping (Figure 4-4). The tools include: dynamic, unclassified choropleth maps; dynamic bars; choropleth maps with dynamic classification and dynamic focusing on a value sub-range of a numeric variable; bar charts and pie charts for vector-based data; and processing of grid data (e.g. elevation models or forest density maps). The EFIS Visualization Toolkit utilizes Common GIS, which is a web-enabled collection of tools for interactive thematic mapping, exploratory visualization, and data analysis (Andrienko et al. 2003).

5.6 Artificial neural networks and fuzzy logic

In the context of ecology and natural-resource management, uncertain information and variables that do not permit simple yes-or-no classification are rather common. Artificial neural networks and fuzzy logic can be used to make decisions for situations in which uncertainty is a significant factor. Neural networks are systems inspired by biological nervous systems that process information by passing data between many simple processing elements. Computing systems mimic the brain through a network of highly interconnected processing elements, thus giving them learning abilities, and enabling them to recognize, and to understand, subtle or complex patterns[8]. Fuzzy logic provides an approach to approximate reasoning, in which the rules of inference are approximate rather than exact. Fuzzy logic is useful in manipulating information that is incomplete, imprecise, or unreliable. Fuzzy logic extends the simple Boolean operators, can express implication, and is used extensively in Artificial Intelligence (AI) programs. Fuzzy logic allows computers to work more easily with concepts such as "fairly," "rarely," or "almost."[9] In the context of information systems, neural networks and fuzzy logic are important because they support structuring and analyses of large data sets that are subject to uncertainty.



☑ group by classes Sort by: total_employed_in_Agricu Descending ☑ TableLens ☑ condensed

Alignment: Means and Std.deviations

Administrative division: %_of_students_at_university_1991

0.110 0.555 0.735 0.945 1.275 4.410

Statistical quality

Quality of the classification = 74.9 %

Quality Vs. best for 5 classes = 27.3 %

Errors computed by: mean

Classification statistics

18.5% 28.7% 20.4% 28.4% 20.0% %_of_students_a

7.5% 10.4% 14.1% 14.8% 53.5% total_pop_1991

☑ Broadcast classification

Attribute: Students_at_universi

☐ invert attribute values

● Perspective

○ Parallel orthographic

☑ Stretch in Z-dimension

☑ Dynamic update

☐ Projection lines

☑ Bounding frame

☑ Points vs. polygons

Figure 4-4. Screenshot of a variety of simultaneously open and dynamically linked displays of an example data set (examples shown: classified choropleth maps, graphical analysis tools including scatter plot matrix and parallel coordinate plot, bar charts grouped by classes, and 3D display).

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[8] http://www.japaninc.net; http://www-agecon.ag.ohio-state.edu/class/AEDE601/glossary/glossa.htm

[9] http://stott.feis.herts.ac.uk/support/technical_glossary.htm

5.7 Integration

Integration is an essential task in reasoning about the environment. In addition to issues around the integration of systems (such as the integration of databases, or simulation systems), there are also challenges related to integrating different players and fields of expertise that remain to be solved. The additional integration of isolated solutions as well as the integration of methods and data require innovative approaches.

The need to organize the wealth of on-line information has been apparent for some time and much has been learned from the library profession in this respect. In the same way that subject libraries organize paper documents using classification systems and card indices, subject specific content on the WWW can be catalogued and linked to subject gateways. In the forest domain, a number of subject gateways exist including the WWW Virtual Library for Forestry (http://www.metla.fi/info/vlib/Forestry), and BIOME/ AgriFor (http://agrifor.ac.uk/).

Subject gateways tend to catalogue information at a high level (e.g. organizations or information services/web pages within an organization's web site), rather than at the level of individual data sets. Furthermore, subject gateways tend to be centralized services organized by intermediate third-parties that are neither directly data providers nor data users.

An alternative approach to the subject gateway approach is for organizations to compile catalogues of their own data and information resources. This maintains a close relationship between the catalogue and the data and allows organizations to more easily control access to and presentation of their data and information resources. If many organizations compile discrete catalogues of forest information there will be a diverse range of data and information to be catered for. To enable effective searching across these catalogues, it is necessary to have standardized descriptors.

This distributed model is similar to that adopted by GFIS (Richards and Reynolds 1999; Päivinen et al. 1998, 1999, 2000; Saarikko et al. 2000). It is composed of a network of catalogues that catalogue information resources using a common metadata standard.

5.8 Other relevant methods

Among the other relevant methods used for the design and implementation of information systems are remote sensing and image analysis, which provide geo-referenced data and facilitate environmental monitoring and planning. The availability of distributed databases, data warehouses and method bases as well as their accessibility via the internet makes computer networking a substantial component and challenge for information systems.

6. CONCLUSIONS

Sustainable management of forest ecosystems requires decisions that integrate a diversity of specialized types of knowledge and that are subject to long term impacts. Forest information systems are a modern tool that provides decision makers with comprehensive information and results in better management decisions. The increasing amount of available data, the need for spatial reasoning, the desire to share distributed information, and the impressive potential of modern computer technology need to be made available for the thorough management of forests. Forest information systems offer the potential for informed decisions and support the maintenance and enhancement of the multiple forest functions. However, problems on the semantic level are much harder to be solved than the technical problems.

ACKNOWLEDGMENTS

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Chapter 5

ROAD AND HARVESTING PLANNING AND OPERATIONS[*]

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Abstract: Road and harvest planning and operations are undergoing rapid changes with improved access to terrain and vegetation data, advancements in computer algorithms, computer hardware and communications. Key technologies are LIDAR (light distance and ranging), global positioning systems, geographic information systems, development of powerful optimization techniques, smaller and faster computers, larger and faster computer memories, and availability of wireless communications.

Key words: Road planning; harvest planning; harvest simulation; optimal tree bucking; forest operations; mechanized harvesting.

1. INTRODUCTION

Road and harvest planners have been early users of computer applications due to the large amount of data to be manipulated. Road and harvest planning begin with an understanding of the terrain. A topographic map combining contour information with planimetric detail has been essential to develop gradelines for route location, estimating earthwork volumes for road construction, and developing ground profiles for locating landings, skid roads, and cable corridors.

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[*] The US Government's right to retain a non-exclusive, royalty-free licence in and to any copyright is acknowledged.

G. Shao and K. M. Reynolds (eds.), Computer Applications in Sustainable Forest Management: Including Perspectives on Collaboration and Integration, 83–99.

From the early 1960s to the 1990s, topographic maps were developed using photogrammetric techniques. Prior to global positioning systems (GPS), photogrammetry utilized stereo aerial photography in conjunction with field survey ground control to produce three dimensional models of the ground. With blocks of photography, an aerial triangulation process was carried out on the blocks prior to data capture. This process populated the stereo model with additional image tie-points, ensuring that each stereo model, and hence the data extracted from it, was created to the required accuracy. One obstacle in forested terrain was the inability to "see" the ground surface, so the three-dimensional model was often a map of the vegetation surface, with the ground surface inferred from a correction to the vegetation surface. With the establishment of satellite-based GPS, ground control has shifted to GPS-gathered ground points.

During the 1990s, laser scanning of terrain, combining aerial platforms (fixed wing and helicopters) and GPS, became commercially feasible for collecting both the vegetation surface and the ground surface. LIDAR (Light Distance and Ranging) emits pulses of light and calculates distance based on the time it takes for the light to return. With a high number of light pulses, some pulses (hits) strike all levels of the canopy from the top height to the ground. Combining this data with GPS provides information about both the top of the vegetation surface (first return), intermediate surfaces (second and following returns), and the ground surface (last return) (Reutebuch et al. 2003a). LIDAR elevation data is ideally suited for mapping extensive areas where very high-accuracy elevation data is required rapidly. Typically LIDAR data is acquired at about 1-m spatial resolution with a height accuracy of about 10 to 20 cm.

2. FOREST ROAD DESIGN AND LOCATION PLANNING

With the advent of high-quality digital terrain models (DTM) constructed from LIDAR data, rapid advances in road planning are now possible. Road design has traditionally been performed by projecting a preliminary grade line on a contour map, followed by field investigation and flagging, or staking a preliminary line through the forest. Data taken at right angles from the line provided designers with data for road design including small shifts in the road centerline. With the development of DTM and geographic information systems (GIS), computer-based methods of route projection such as PEGGER (Rogers 2005) have been developed. The system works as an extension to the widely used GIS software of ArcView (Figure 5-1). The design procedure automates the traditional paper-based route-projection process, and generates survey data by imitating the actual methods used by a field crew. Then, the preliminary road location and survey data are exported into one of the currently used forest-road-design systems such as RoadEng (2002) to produce the final road location (Figure 5-2).

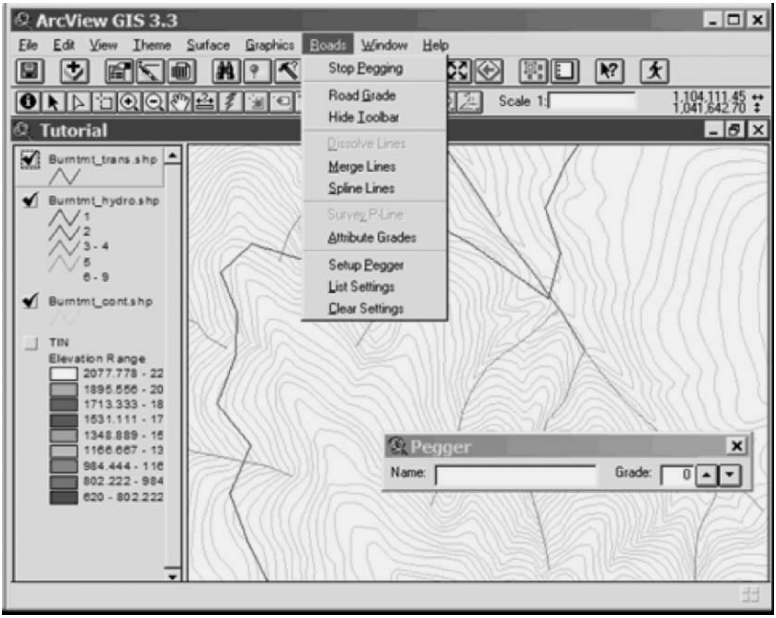
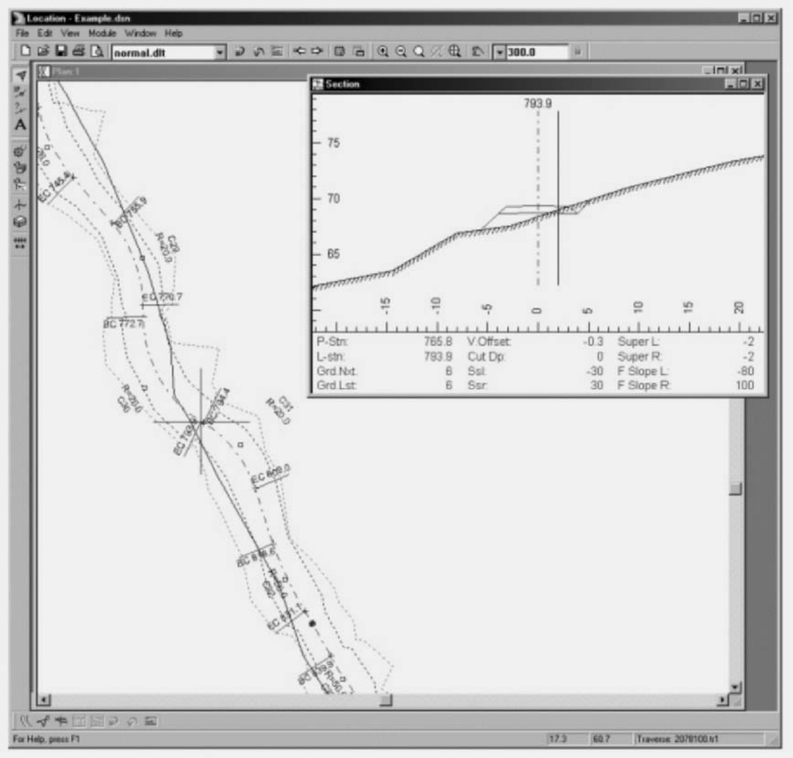


Figure 5-1. The user interface of PEGGER in ArcView environment (Rogers 2005).

The system uses ROADVIEW, a road visualization package for ArcView, to display an approximate 3D view of the preliminary alignment of a forest road. Even though the system was not designed to generate an optimum road alignment, it can still assist a forest-road designer in efficiently and quickly analyzing many road alternatives using GIS technology.

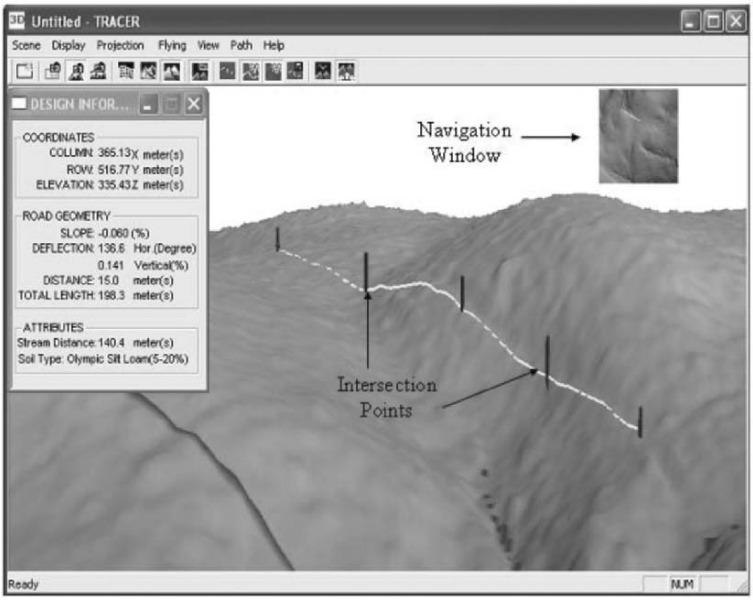
Akay and Sessions (2005) and Aruga et al. (2005a, 2005b) showed that modern computerized computational techniques, combined with high-quality DTM, could be used for computerized optimal design of forest roads, increasing designer productivity and reducing costs (Figure 5-3). Shifts in horizontal and vertical alignment could be considered simultaneously, and earthwork balanced optimally through mathematical optimization, thus reducing road construction costs and environmental effects (Aruga et al. 2005c, 2006).



P-Stn:	765.8	V.Offset:	-0.3	Super L:	-2
L-stn:	793.9	Cut Dp:	0	Super R:	-2
Grd.Nxt:	6	Ssl:	-30	F Slope L:	-80
Grd.Lst:	6	Ssr:	30	F Slope R:	100

Figure 5-2. Plan and cross-section windows of RoadEng program (from http://www.softree.com/products/location_forest_pro.htm).

Existing computerized planning techniques for locating roads follow one of two approaches. The first approach uses a raster representation of terrain and finds alternative routes by connecting neighboring grid cells. In this approach, a node represents a grid cell and a link represents a road connecting two adjacent grid cells. Chung and Sessions (2001) optimized a road network using a DTM by considering 8 alternative road directions from each grid cell. Heinimann et al. (2003) later improved the road-routing procedure by considering 24 road links from one node (Figure 5-4). The second approach uses a vector representation of road links, and determines the best road locations among alternatives. NETWORK2000 (Chung and Sessions 2003b) has been used to determine resource-transportation routes, as well as road locations using the vector representation of alternative road networks (Figure 5-5) (Plate 5-5). Anderson and Nelson (2004) also developed a computer algorithm to automatically generate vector-based road networks for strategic planning.



COORDINATES
COLUMN: 365.13X meter(s)
ROW: 516.77Y meter(s)
ELEVATION: 335.43Z meter(s)

ROAD GEOMETRY
SLOPE: -0.060 (%)
DEFLECTION: 136.6 Hor.(Degree)
0.141 Vertical(%)
DISTANCE: 15.0 meter(s)
TOTAL LENGTH: 198.3 meter(s)

ATTRIBUTES
Stream Distance: 140.4 meter(s)
Soil Type: Olympic Silt Loam(5-20%)

Figure 5-3. Initial path of road, located on 3D view of terrain (adapted from Akay and Sessions 2005).

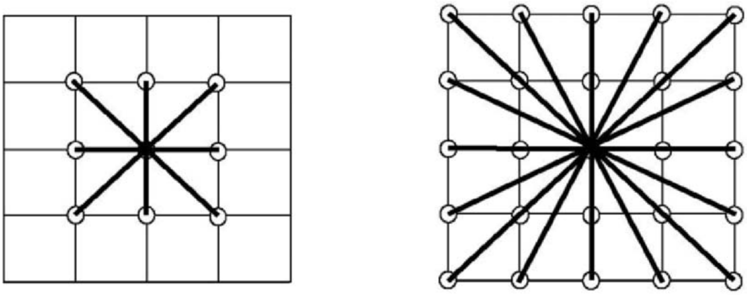


Figure 5-4. Considering 8- or 24-road links to neighboring nodes in road-location planning with a DTM.

3. HARVEST PLANNING

Similar advances are being made in harvest planning in steeper terrain. Harvest planning in steep terrain requires terrain analysis to evaluate the physical feasibility of forest operations and to determine costs.

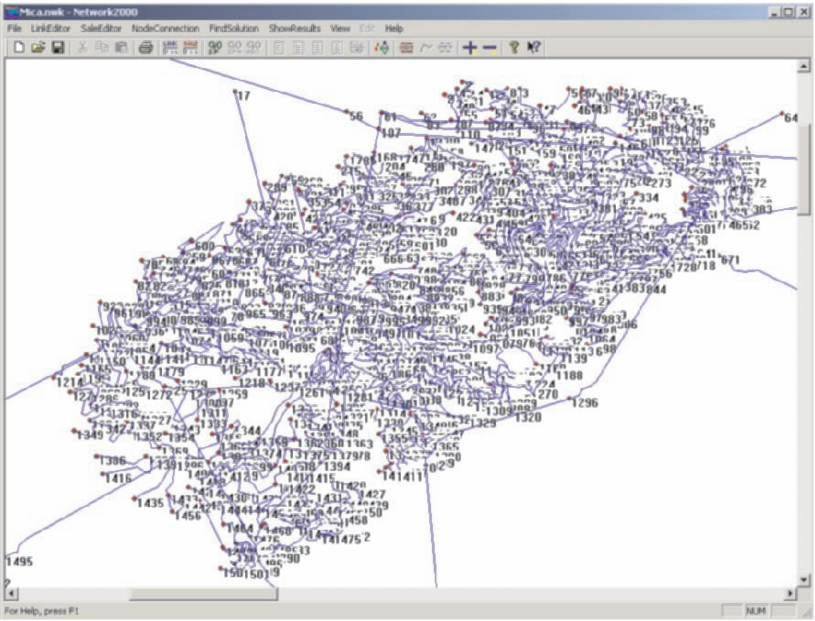


Figure 5-5. Vector-based road networks shown in NETWORK2000. (See also color plate 5-5 on p. CP7)

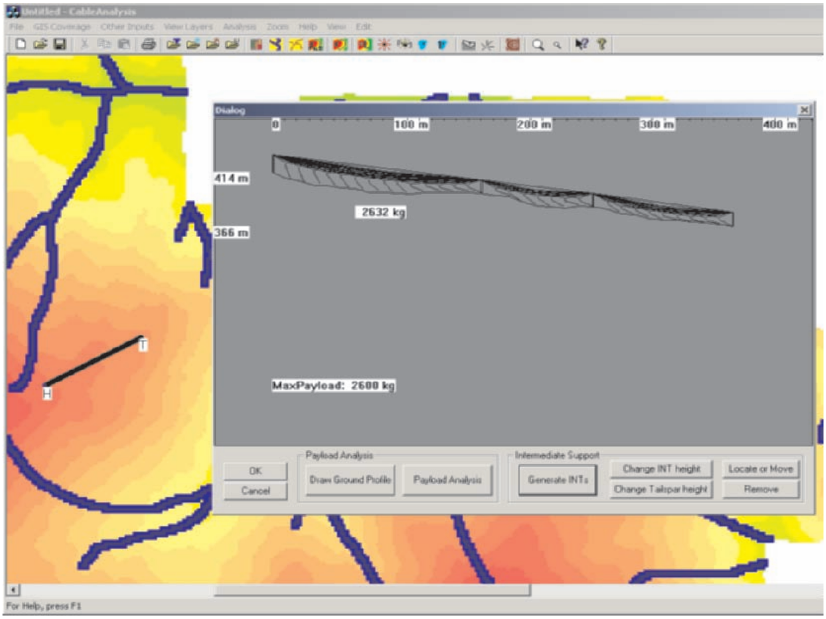


Figure 5-6. Cable-logging profile being analyzed for use with an intermediate support (Chung and Sessions 2003). (See also color plate 5-6 on p. CP7)

In the 1960s, data for profile analysis of cable corridors was done using data collected from ground surveys and rough contour maps, and analyses were performed using mainframe computers. With development of personal computers, analysis packages such as LOGGERPC (Jarmer and Sessions 1992) became standard, but data was still collected and input manually. With the development of DTM, analysis software is moving rapidly forward. The logging-plan model, PLANS (Twito et al. 1987), was an early effort to simulate and evaluate alternative harvest plans using DTM. Recent efforts integrate modern cable-logging planning algorithms, DTM, and optimization algorithms to develop harvest plans in steep terrain. Examples include CableAnalysis (Chung and Sessions 2003a), PLANEX (Epstein et al. 2005), and CPLAN (Chung et al. 2004). CableAnalysis is a terrain analysis tool to evaluate the physical feasibility of cable logging operations. It implements a series of computer algorithms to extract topographic information from a DTM, analyzes payload and ground profiles, and finds acceptable intermediate support locations (Figure 5-6) (Plate 5-6). Simultaneous optimization of harvest-equipment location and road-access location becomes available with more sophisticated harvest-planning tools such as PLANEX and CPLAN. PLANEX (Epstein et al. 2005) identifies appropriate harvesting methods according to ground slopes and sequentially determines landing and road locations to minimize logging costs that include harvesting, road-building, and transportation costs (Figure 5-7) (Plate 5-7). CPLAN (Chung et al. 2004) solves a similar problem using a network algorithm that includes consideration of cable-logging feasibility (Figure 5-8) (Plate 5-8).

With increased use of LIDAR and development of linkages between LIDAR data sets and characteristics of individual tree such as crown width, it is possible to estimate diameter and volume, in addition to height, of individual trees (Maltamo et al. 2004). Because LIDAR provides the actual locations of dominant trees, the location of suitable trees for cableway supports may soon be done automatically, rather than by more time-consuming manual use of aerial photographs. The availability of accurate harvest-tree volume and locations in 3D space will enable us to conduct more precise planning for landing, skid roads, cable corridors, and road locations. This will eventually help to reduce environmental impacts and increase work and cost efficiencies of forest operations.

Computer-aided harvest planning models for other steep terrain harvesting systems including helicopter and balloon logging have been developed. The most common computer-aided harvest planning tool for helicopter logging is HELIPACE (USDA Forest Service 2005). Another helicopter logging planning tool is included in the LOGCOST program (USDA Forest Service 2005). Both are non-spatial and do not include optimization. Balloon logging is not currently operational and planning program support has been discontinued.

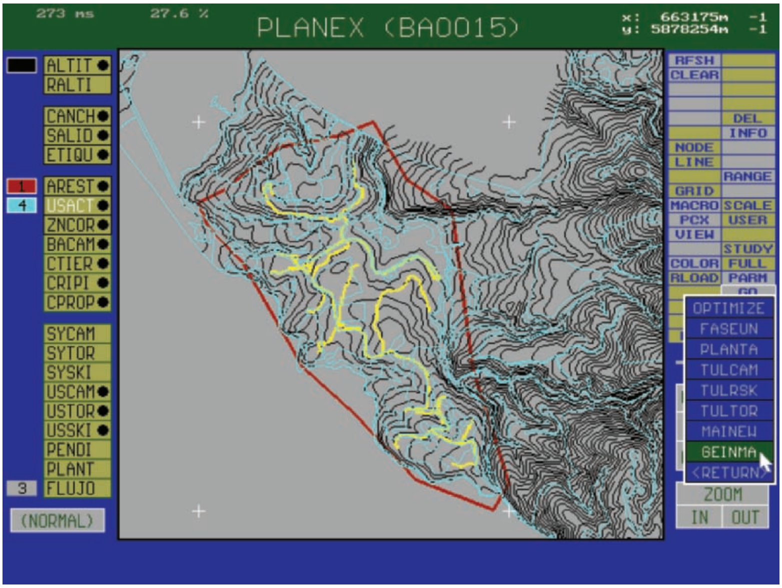


Figure 5-7. The user interface of PLANEX, showing a graphical solution for road network and timber flow. (See also color plate 5-7 on p. CP8)

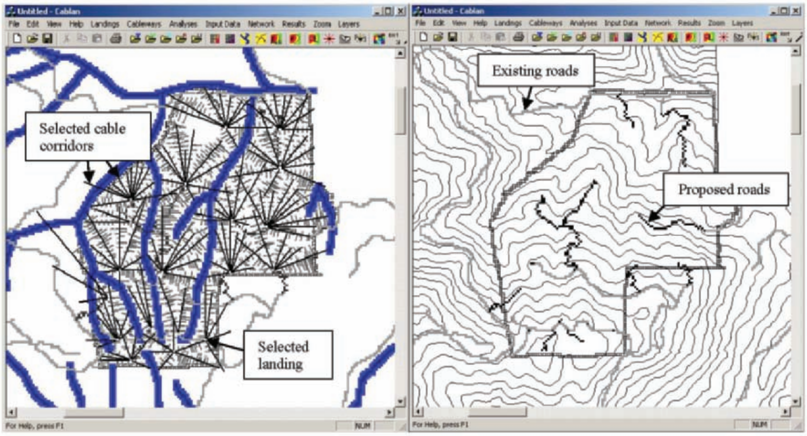


Figure 5-8. A harvesting plan produced by optimizing road, landing, and cable-corridor locations using CPLAN. Figure 5-8a (left) shows landing and cable corridors. Figure 5-8b shows road segments that must be constructed. (See also color plate 5-8 on p. CP8)

Several computer models have been developed to predict mobility and productivity for ground-based logging systems. One program, SkidPC 2000 (Spong 2001), considers tracked and rubber-tired skidder and forwarder mobility as a function of trail conditions including slope, soil strength, and logging slash. Another program, Setting Analyst (Halleux and Greene 2003), is an ArcView extension that facilitates harvest planning by comparing different harvest settings based on projected average skidding distance, logging costs, and site disturbance levels. Both SkidPC and Setting Analyst are simulation programs without optimization.

4. HARVESTING OPERATIONS

4.1 Computer simulation

Computer simulation has been used to analyze timber harvesting and transport operations since the 1960s (Newnham 1968, Bradley and Winsauer 1976, Goulet et al. 1979). Computer simulation has the advantage of being able to model the complexity of various harvesting systems. Computer simulation of harvest production on steep ground began in the early 1970s. Sessions (1979) developed YARDALL to simulate yarding logs from trees felled on steep hillsides. Using computer simulation, the computer program could harvest a stand using a set of rules or a human participant could “yard” each turn based upon equipment characteristics, physical feasibility, and log availability. This work was extended by Ledoux and Butler (1981), McGaughey (1983), and McGaughey and Twito (1985). Human participation in harvest simulation increased in the 1980s. Fridley et al. (1985) used graphical interactive swing-to-tree feller-buncher simulation to study equipment design in thinnings. Greene and Lanford (1986) and Greene et al. (1987) examined drive-to-tree feller-bunchers using computer simulation. Recent simulations have focused on modeling harvesters, forwarders, and grapple skidders. Examples include McNeel and Rutherford (1994), Aedo-Ortiz et al. (1997), Eliasson (1999), Wang and Greene (1999), and Wang et al. (2005). Increasingly sophisticated graphical harvest simulators have been developed by equipment manufacturers, both to improve equipment design, as well as to train operators on forest equipment (Figure 5-9). Using stand generators, tree spacing is assumed to be either uniform or random, or in some cases is based on actual, observed locations taken from a representative part of the stand. With the availability of LIDAR, actual tree locations can be mapped, providing the ability to examine the performance of a harvest system in actual stands under a variety of silvicultural prescriptions. Sessions and Chung (2003) combined locations of tree stems on a DTM, helicopter performance characteristics, and road and landing options to determine optimal road systems for helicopter logging. Implementation schedules combining log availability, pressure-altitude, elevation, fuel-on-board, and GPS were proposed.

Figure 5-9. Harvest simulator used for training machine operators.

In many modern forest operations on flatter terrain, loggers have been removed from the forest floor. Trees are felled, crosscut into logs, extracted to roadside, loaded on to trucks, weight scaled, and unloaded at the mill without a logger on the ground. Prototypes of computer-controlled walking machines have been developed for felling on steeper terrain. A research goal of having "no man in the woods" appears achievable given rapidly emerging robotic and digital technologies (Skogforsk 2004). Already, use of GPS, combined with GIS, are being used to control trucks hauling ore from pit to stock piles in the mining industry, and to guide manual control of harvest machines in agriculture and helicopter spray applications of tree nutrients in forestry.

4.2 Real-time decision making – optimizing in-woods log processing

Beginning in the 1970s, computer optimization of individual-tree bucking patterns began. Following the dynamic programming applications of Pnevmaticos and Mann (1972), a number of researchers developed computer algorithms to solve the best way to divide a tree into logs given economic criteria.

Developments can be divided into three areas (1) research to develop specific bucking rules to be given to manual cutters and or mechanized machine operators, (2) research to develop tools to monitor manual or mechanized cutters, and (3) algorithms to develop bucking patterns to be used interactively by optimizing calipers or by harvest machines.

VISION, was developed by Weyerhaeuser Company (Lembersky and Chi (1984) to improve the quality of tree-bucking instructions and to allow operators to improve their decision-making skill. AVIS, developed by the Forestry Research Institute of New Zealand (Geerts and Twaddle 1985) was used in both monitoring log manufacturing and training cutters. BUCK, developed at Oregon State University (Sessions et al. 1988), is an interactive tree optimizer based on network analysis that considered alternative mill prices, transport distances, and equipment capability. The program was run on a desktop computer and could process batches of trees automatically or with human participation using interactive graphics. BUCK could also be run at the stump using all-weather handheld computers (Sessions et al. 1989) and was tested on a mechanized harvester (Olsen et al. 1991). Programs such as those by Pickens et al. (1992) have been developed for determining optimal bucking patterns for hardwoods in the eastern United States, and for hardwoods and softwoods in northeast China (Wang 1995, Wang et al. 2004).

Figure 5-10. Inside the cab of a modern harvester with sensing, computing, and communications technologies (Courtesy of Ponsse Oy).

In the late 1980s, the Forestry Research Institute of New Zealand developed a set of prototype ultrasonic, optimizing calipers. Lengths and diameters were measured ultrasonically. Quality characteristics were entered via a keyboard. Optimal bucking was done on a portable computer. This prototype led to the development of commercial optimal bucking calipers that were used successfully in New Zealand for almost a decade. Modern harvest machines (Figure 5-10) now use on-board computers to decide the bucking pattern, combining tree characteristics measured during de-limbing with either a set of log prices defined by length and diameter, or a set of bucking orders. In the case of bucking orders, computer algorithms have been used to determine the best set of log orders, and in some cases logging crews, to be assigned to each stand, given a set of customer orders (Murphy 1998, Kivinen 2005).

A number of technologies have been evaluated for assessing external characteristics of felled tree stems, including laser profiling, optical methods and microwaves. Tian (1999) outlines the advantages and disadvantages of these technologies and concludes that optical systems show the greatest promise for detection of external knots. Tian et al. (1997) describe a computer vision system, based on texture analysis, for the detection of trimmed and occluded knots on freshly harvested tree stems with bark that could have application on a mechanized processor.

Increasingly sophisticated tree-stem models are developed with the ultimate goal being, in real time, to describe the 3D form as well as determine branch size and frequency. In an effort to reduce variability in the performance of products made from logs, more attention is being paid to internal stem characteristics. X-ray and RADAR technologies have been successfully demonstrated by researchers in the United States and Sweden for assessing internal characteristics such as knotty core and rot (Rayner 2001, Kaestner et al. 2000). Industrial Research Limited in New Zealand has developed a tool that uses sound to assess the stiffness and fiber properties of logs (IRL 2002). Kelley et al. (2001) have shown that near-infrared spectroscopy could be used in the field to measure such characteristics as moisture content, density, spiral grain, and extractives content. It is highly likely that some of these technologies will eventually become part of the measuring systems used on mechanized processors.

Radio communications between the harvester and mill can pass log-inventory information from the harvester to the mill, and prices or log-order updates from the mill to the harvester.

Having incurred the cost to fell trees, accurately measure their external and internal characteristics, and buck them into logs suited for the most appropriate markets, it is important that the logs reach the customers for which they were intended. Providing a platform for new technologies for tagging and tracking logs is one of the opportunities that mechanization opens up for the forest industry. Bar-coding of logs is the most viable option for tagging logs at this stage, but there are problems with attaching bar-codes at the time the logs are bucked. Other technologies, such as radio-frequency tagging and aroma tagging, may provide a viable alternative (Murphy and Franich 2004).

Nondestructive testing of tree stems has long been used in sampling to estimate tree properties of forest stands. Now, with measurement capabilities on harvesters and mechanized de-limbers, it is possible to collect stem data during harvesting to refine stand-inventory data on stands not yet harvested (Stendahl and Dahlin 2002, Murphy et al. 2005). Increasing accuracy of GPS (Reutebuch et al. 2003b) will allow improved spatial estimates to be linked to harvester stem data. In a separate but related effort, within-stand use of digital photography, combined with principles of photogrammetry, are being examined to understand tree form, branch size, and frequency in an effort to better predict stand value (Firth et al. 2000).

5. ROAD OPERATIONS

The transport of log stocks from the field to mill yards uses principles of network analysis, GPS, and optimization techniques to develop, monitor, and assign trucks. GPS is also being used to track trucks on narrow forest roads to improve safety.

Adjustment of tire pressure can improve truck performance, as well as reduce road maintenance and sedimentation (Brown and Sessions 1999). Variable tire-inflation systems have the potential to be combined with GPS and GIS to automatically adjust tire pressures along haul routes so that truck performance is optimized.

Road maintenance is a significant component of timber transport costs on unpaved roads, sometimes exceeding the actual trucking cost. Rough roads reduce productivity, increase truck-maintenance costs, increase sedimentation from forest roads, and increase stress on truck operators. Road-management systems rely on the availability of quality information to make good decisions on the allocation of road-maintenance equipment and materials to maintain smooth forest roads. Recent advancements in accelerometer technology, combined with one of a variety of non-contact measurement devices (lasers, infrared, or ultrasound), GPS, and computerized data loggers, provide the ability to measure road roughness at operating speeds. One such system attaches road-roughness sensors to logging trucks (Brown et al. 2003). Road-roughness information is captured as the trucks travel the forest roads, and is downloaded at the mill yard. Data is then interpreted and road-maintenance equipment allocated.

6. CONCLUDING COMMENTS

Emerging technologies are rapidly improving terrain and tree data that will form the basis for making better decisions in road and harvest planning and operations. Improved terrain and tree data are key to making optimization of road and harvesting operations valuable. Optimization of forest operations is a sought-after goal, but optimizing road design, equipment location, or tree bucking with imprecise data may not lead to improved decision making. Without good data, one could argue it is better to solve a real problem in the woods without necessarily the best solution, rather than trying to implement an optimal solution based on poor data.

There is emerging evidence that digital measurements from LIDAR-based DTM are superior to field measurements using common field instruments. Tests to determine if field-ready road designs can be developed in the office from remotely sensed data and implemented with GPS devices are in progress. Development of increasingly powerful field quality computing devices coupled with GPS promise to improve data collection, analysis, and decision support in the field.

Forest engineers and operations foresters will increasingly rely on digital tools. Undergraduate education now routinely includes training in GIS, GPS, and CAD (computer aided design) technologies. Decision support software will increasingly become accessible as seamless interfaces to commonly used GIS platforms are developed.

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Chapter 6

FOREST SIMULATION MODELS

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Abstract: Sustainable forest management represents a paradigm for forestry. Traditional forestry objectives aimed at sustainable yield are being replaced with those of sustainable ecosystem management. Such a shift in forest management requires an effective transfer of results from forest researchers to managers. In order to predict the potential impacts of changes in environment (such as climate, land–use, fire disturbance and forest harvesting) on the sustainability of forest ecosystems, forest resource managers will require forest simulation models. Forest simulation models have a long history in forestry and have proven to be useful tools for forest management. There have been two basic approaches to modeling forest growth and dynamics: empirical and mechanistic forest simulation models. This chapter reviews and compares four major types of forest simulation models: (1) growth and yield models (empirical approach), (2) succession models (empirical–mechanistic hybrid approach), (3) process models (mechanistic approach), and (4) hybrid models. Their applications are described in four case studies. The advantages and disadvantages of the different modeling approaches are discussed. Case studies deal with predicting future forest conditions under different management options, simulating the potential effects of climate change, and effects of fire disturbance on structure and function of forest ecosystems in Canada. There is still a gap between foresters and ecologists in developing and using forest simulation models. There will not be a single, super model that will satisfy all of the diverse demands and purposes simultaneously. Diversified modeling approaches integrated into a decision-support system, an important tool for evaluating the sustainability of forest ecosystem in a changing environment, are emphasized.

Key words: Forest modeling; growth and yield model; succession model, process model; hybrid model; sustainable forest management; ecosystem sustainability.

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1. INTRODUCTION

Awareness of the need for environmentally sustainable economic development was raised by the widely cited Brundtland report Our Common Future (WCED 1987). Published over a decade ago, issues identified in the report - including sustainable development - remain as unmet challenges. The Brundtland report defines sustainable development in terms of inter-generation equity as "ensuring that (humanity) meets the need of the present without compromising the ability of future generations to meet their own" (WCED 1987). Sustainable development was the major focus of international attention in Agenda 21, set up at the Earth Summit held in Rio De Janeiro in 1992. As a result of the Rio meeting, some national governments have responded to the call to establish sustainable development strategies (CCFM 1992, HMSO 1994). The ongoing debate on sustainable development has moved from defining this broad concept to examining ways in which it can be measured (Cocklin 1989, Bossel 1996, Wardoyo and Jordan 1996, CCFM 1997, Morris et al. 1997, Peng et al. 2002).

Today's managers of forest resources face a number of important challenges. One of the most critical is the need to provide forest products for an increasing world population despite a shrinking natural-resource base challenged by climate change, desertification, environmental pollution, loss of biodiversity and other stresses. Social and political pressures require that forest management meet these challenges in an ethical and economical fashion, ensuring environmental stewardship and sustainable productivity. Sustainable forest management represents a paradigm for forestry (CCFM 1992), and involves management of both temporal and spatial patterns of ecosystem conditions at both stand and landscape levels. Traditionally, forest science has focused on stand-level processes, and the prediction of forest growth and yield has been through use of the historical bioassay (Kimmins 1990). Many contemporary issues related to climate change, ecosystem conservation, biodiversity, and sustainable management, however, cannot be handled solely at the stand level, and do not have historical analogues for their solution (Kimmins 1997, Landsberg and Waring 1997). Rather, the issues are at landscape level, and related to the patterns of change at various spatial and temporal scales. One particular challenge is to predict the long-term and broad-scale response of forests to a rapidly changing environment, and to transfer these research results to forest managers, policy makers, and the public.

Forests are dynamic ecosystems that are continuously changing. To obtain relevant information for decision making, it is necessary to project these changes. Forest management decisions are based on information about both current and future resources conditions. In the absence of long-term field data, forest simulation models that describe forest dynamics (i.e., growth, succession, mortality, reproduction, and associated stand changes) have been widely used in forest management to update inventory, and to predict future yield, species composition, and ecosystem structure and function under changing environmental conditions. They also allow exploration of management options and silvicultural alternatives, and provide information for sound decision making (Shugart 1984, Botkin 1993, Vanclay 1994). Consequently, predicting future forest growth and yield under different management scenarios is one of the most important issues of sustainable forest management.

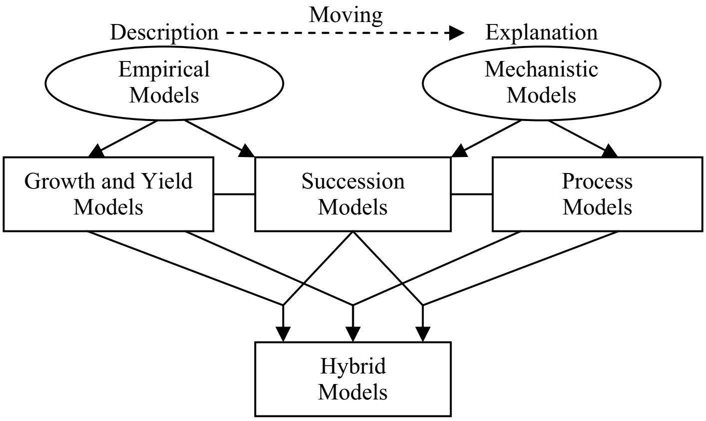

Figure 6-1. Categories and features of forest simulation models used in forest management (modified from Peng, 2000).

Forest-growth modeling has a long history in forestry. As early as the 1850s, central European foresters used graphical methods to model the growth and yield of forests (Vukila 1965). The development of computerized simulation models for forest growth and management dates back to early the 1960s (Newnham 1964). During the past decades, there have been many papers discussing various types of forest simulations models (e.g., Kimmins 1990, Bossel 1991, Vanclay 1995, Korzukhin et al. 1996, Shugart et al. 1996, Battaglia and Stand 1998, Peng 2000, Mäkelä et al. 2000, Landsberg 2003). Although the design and output variables of these models may vary, they fall into four main categories (Figure 6-1): growth and yield models, succession models (gap models), process models, and hybrid models. Depending on the extent to which an understanding of process is incorporated, forest simulation models can be classified as either empirical or mechanistic. Because there is a continuum across the range, the term hybrid is used for models that provide some explanation of processes influencing tree growth. This chapter briefly reviews and discusses the four major types of forest simulation models useful for sustainable forest management.

2. FOREST SIMULATION MODELS

There are three approaches to assess the effects of changing environmental on forest dynamics (Botkin 1993): (1) our knowledge of the past, (2) present measurements, and (3) our ability to project into the future. Our knowledge of the past and present measurements is potentially important, but has been of limited use. Long-term monitoring of the forest has proven difficult due to costs and the need for long-term commitment of individuals and institutions. Because the response of temporal and spatial patterns of forest structure and function to changing environment involves complicated biological and ecological mechanisms, current experimental techniques are not directly applicable. In contrast, models provide a means of formalizing a set of hypotheses.

2.1 Forest growth and yield models

The origins of modern forest simulation systems lie in the development of yield table by mensurationists in Germany in the late 18th century (Vuokila 1965). Extensive collection of forest inventory data and estimates of existing timber volumes have led to development of growth and yield models as effective prediction tools for even-age forest management since the last century. Much progress in uneven-aged forest growth and yield modeling has occurred since the first predictive models were pioneered by Moser and Hall (1969). Since then, a wide variety of models has been developed for predicting forest growth and yield at both the individual tree and stand level. Over time, the general level of sophistication of these models has grown owing to many factors, including more refined statistical estimation techniques, expanding databases, better understanding of forest dynamics, and the burgeoning power and availability of computers. For example, the Forest Vegetation Simulator (FVS), a well established model, is a useful tool for predicting forest stand dynamics, and is applied extensively in the United States (Teck et al. 1996, Dixon 2002). FVS descended from the Prognosis model, which was conceived by Al Stage (1973), and developed for forest conditions in the northern Rocky Mountains. At present, there are more than 20 variants that represent conditions in a majority of forest ecosystems in the U.S. forest managers have used FVS extensively to summarize current stand conditions, predict future stand conditions under various management regimes, and update inventory statistics. Growth and yield methodology for forest stand management has incorporated a variety of techniques: (1) stand-level models (Leak 1964, Moser and Hall 1969, Murphy and Farrar 1982 and1983, Murphy and Farrar 1985), (2) systems of equations (Moser 1972, 1974, Leary et al. 1979, McTague and Stansfield 1994), (3) nonlinear stand-table projections (Ek 1974, Adams and Ek 1974), (4) Markov chains (Bruner and Moser 1973, Frazier 1978); (5) matrix models (Buongiorno and Michie 1980, Solomon and Hosmer 1986, Solomon et al. 1995, Favrichon 1998), and (6) artificial-neural-network techniques (Guan and Gertner 1991a, 1991b, 1995; Keller et al. 1997). An overview of growth and yield developments can be found in Knoebel et al. (1986), Kimmins (1993), and Peng (2000).

Most empirical growth and yield models used a site index to determine the potential or maximum growth rate (Clutter et al. 1983, Vanclay 1995). In addition to site indices, a number of growth and yield models have used competition indices to measure competition effects of adjacent trees, and incorporated these into predictive models to estimate individual-tree growth (Newnham 1964, Monserud 1975, Hix 1990, Shao and Shugart 1997). Empirical forest growth and yield models are derived from large amounts of field data, and describe growth rate as a regression function of variables such as site index, age, tree density, and basal area. Most growth and yield models rely on the process of production, in which a set of simulation system inputs and outputs are observed, recorded, and measured, and some or all of the mathematical models are inferred. These empirical models are based on massive experimentation or inventory in which the available input and output data are accepted as the most appropriate. The major strength of the empirical approach is in describing the best relationship between the measured data and the growth-determining variables using a specified mathematical function or curve. In implementation, empirical models require only simple inputs, and are easily constructed. They are also easily incorporated into various management analyses and silvicultural treatments, and are able to achieve greater efficiency and accuracy in providing quantitative information for forest management. They may be an appropriate method for predicting short-term yield for time scales over which historical growth conditions are not expected to change significantly. Most growth and yield models cannot be used, for example, to analyze the consequences of climatic changes or environmental stress as climate is ignored as a determinant of forest growth (Kimmins 1990, Shugart et al. 1996, Peng 2000). In addition, growth and yield model development has not yet been integrated with uneven-aged management regulation techniques (Peng, 2000). Forest management for uneven-aged stands is hampered by a lack of adequate growth and yield information, likely due to (1) lack of interest in uneven-aged management in the past, (2) scarcity of suitable data for research efforts, and (3) difficulties in developing modeling strategies. An improved understanding of the growth and dynamics of uneven-aged stands and improved modeling approaches, such as hybrid modeling, as well as the integration of new computer technologies (object-oriented programming with user-friendly interfaces), tree visualization, and spatially-explicit application of geographic information systems (GIS), will certainly facilitate our ability to project the future growth and yield of forest stands at broad spatial scales (Peng 2000).

2.2 Forest succession models (gap models)

Forest succession (or gap dynamic) models, which incorporate explicit representations of key ecological processes (e.g., establishment, tree growth, competition, death, and nutrient cycling), have been developed for simulating the growth and dynamics of mixed-species and mixed-age stands, and to capture the transient response of vegetation or a simple biome to a changing environment (Shugart and West 1984, Shugart 1984, Botkin 1993). The first such model was JABOWA (Botkin et al. 1972), developed for forests in New England (United States). Over the past decades, gap models have been developed for a wide variety of forest ecosystems (Shugart and West 1980, Shugart 1984, Botkin 1993, Shugart and Smith 1996, Bugmann et al. 2001).

A number of forest succession models have been used to simulate time-dependent changes in species composition and abundance under a changing climate (e.g., Overpeck et al. 1990, Botkin 1993, Bugmann and Solomon 1995, Price and Apps 1996, Price et al. 1999a, b, Bugmann et al. 2001). Several obstacles stand in the way of extensive use of currently available dynamic vegetation models in forest management and global change studies (Linder 2000). For example, most gap-level models are incapable of investigating the consequences of the processes operating on a scale broader than the size of a gap, and hence, interactions among the dynamics of these gap-sized sites were neglected.

It is also impractical to use gap-level models to predict shifts in vegetation beyond those at the local scale because of the large number of points that would have to be simulated. Dynamic models require much more information on the silvical characteristics of species than is easily available or even known for some areas of the globe (Solomon 1986). These forest models have been transformed to predict changes in forest ecosystems at landscape (He et al. 1999) or regional scales (Shao et al. 1995), but have not yet been applied at the global scale (Shugart 1992, Shugart and Smith 1996, Bugmann et al. 2001). Also, the absence of below-ground biomass components in most succession models make them of little use in addressing questions concerning the use of forests to mitigate the atmospheric increase in CO_2. A recent review by Wullscheger et al. (2001) recommended several model improvements including (1) improved multi-layer representations of soil-water and nutrient availability, (2) more accurate information on biomass allocation to roots and root distribution within the soil profile, and (3) improved attention to above- and below-ground processes, all of which could help address intra-specific competition for water among trees of differing size classes. Succession models need to become more process based to address questions about the response of forest growth to changes in climate and CO_2 concentration (Reynolds et al. 2001). Incorporating detailed and mechanistic approaches for regeneration (Price et al. 2001), mortality (Keane et al. 2001, Pastor and Post 1988), and growth and competition dynamics (Norby et al. 2001) into succession models will be a valuable addition.

2.3 Forest process-based models

The term, process model, refers to simulating the structure and functions of a forest ecosystem by mathematical representations of the underlying biological processes controlling the behavior of an ecosystem. The International Biological Program of the late 19960s and early 1970s (Reichle 1981), with its emphasis on understanding and quantitatively describing the key features and dynamics of forested ecosystem structure and function, provided a major boost to the developing field of ecosystem process modeling. Unlike empirical models, mechanistic process-based models generally describe key ecosystem processes, or simulate the dependence of growth on a number of interacting processes, such as photosynthesis, respiration, decomposition, and nutrient cycling. These models offer a framework for testing and generating alternative hypotheses, and have the potential to help us accurately describe how these processes will interact under given environmental changes (Landsberg and Gower 1997, Peng 2000). Consequently, their main advantages are the inclusion of ecophysiological principles, and their long-term forecasting ability within changing environments. Early process models were unable to address time scales that are relevant to traditional forest management issues (i.e. tree crop rotation), and to the analysis of sustainability issues such as multiple crop rotations. With increased understanding of forest ecosystem processes, structure and function, and availability of greatly increased computing power, process models have become increasingly accurate and useful as representations of ecological systems. In addition, process models have the potential to be far more flexible than those based on empirical relationships, and can be used to explain cause and effect. However, they require more field data than empirical models to support complex calibration and validation procedures.

Over the last decade, substantial progress has been made in the development of more mechanistic forest-growth models designed to integrate energy, C, nutrient and hydrologic cycles. Recently, Battaglia and Sands (1998), Landsberg and Coops (1999), Mäkelä et al. (2000) and Peng (2000) have extensively discussed the advantages and disadvantages of using empirical and mechanistic process models in sustainable forest management. Generally, a weakness of one type of model is perceived as a strength of the other, and vice versa. It is almost always possible to find an empirical model that provides a better fit for a given set of data due to the constraints imposed by the assumptions of process models. Nevertheless, empirical and process models can be married into hybrid models in which the shortcomings of both approaches can be overcome to some extent. This is the rationale behind the hybrid simulation approach to forest growth and C dynamics modeling (Kimmins 1993, Battaglia et al. 1999, Kimmins et al. 1999, Peng 2000). Specifically, incorporating the key elements of empirical and process approaches into a hybrid ecosystem modeling approach can result in a model that predicts forest growth, production, and C dynamics in both the short- and longterm (Battaglia and Sands 1998, Kimmins et al. 1999). A valuable summary of process modeling for forest management can be found in Mäkelä and Landsberg (2000). Unfortunately, process models have not yet been studied much in forest management, because they are less able to predict forest structure and yield at a particular site than a conventional growth and yield model developed from historical data from that site (Korzukhin et al. 1996, Landsberg and Gower 1997, Battaglia and Stands 1998, Mäkelä et al. 2000, Zhou et al. 2005).

2.4 Hybrid models

As discussed by Korzukhin et al. (1996), all empirical models have mechanistic elements, and all mechanistic models have empirical elements. To overcome the limitations and gain the advantages of both empirical and process-based models, a hybrid approach can be used to model forest ecosystems. Hybrid models contain both empirical and mechanistic elements at the same hierarchical level. Considering the challenges for forest research such as prediction of growth and dynamics of mixed-species, uneven-aged stands, and the analysis of forest response to future environmental changes, a hybrid approach coupling an empirical growth and yield model with a process-based model may be useful (Peng 2000). In the hybrid approach, physical and physiological mechanics are used to derive model forms that are conditioned to fit common remeasurement data. Some hybrid growth and yield models have recently been developed (Kimmins 1990, 1993, Korol et al. 1994, 1996, Kimmims et al. 1999, Peng et al. 2002). Basic growth and yield models have started to be coupled with rapidly emerging tree-process models whose dynamics are determined by physiological processes (Friend et al. 1993, 1997, Bossel 1996, Landsberg and Waring 1997, Peng et al. 2002). There is a growing recognition of the power of hybrid simulation models used for forest management.

3. APPLICATION OF FOREST SIMULATION MODELS: FOUR CASE STUDIES IN CANADA

Forest simulation models have proven to be useful tools for forest management. Forest simulation models are constructed for many reasons and for a variety of users, including resources managers, ecologists, economists, financial advisers, and students. Theses users may apply forest simulation models for (1) predicting tree volume, (2) optimizing appropriate silvicultural input for maximizing yield, (3) understanding forest succession and competition, (4) assessing impacts of environmental stress such as air pollution, acid rainfall, and climate change, (5) evaluating sustainability of forest ecosystems, (6) testing various hypotheses about tree structure and function, and (7) teaching and education. These diverse objectives involve dynamic processes that vary in time scale from minutes to centuries, and are applicable at spatial scales that range from the leaf to the ecosystem. Comprehensive reviews of model application in forest management are given by Botkin (1993), Vancaly (1995), Shugart and Smith (1996), Newton (1997), Battaglia and Stands (1998), Mäkelä and Landsberg (2000), Lansberg (2003). Four case studies from Canada follow.

3.1 Case I: Red pine (*Pinus resinosa*) density management diagram for Ontario

The Density Management Diagram (DMD) is one of most useful growth and yield modeling tools to assist forest managers in enhancing the volume production of stands. Initially developed by a Japanese scientist in the early 1960s, the DMD is based on the –3/2 power rule (or law) of self-thinning, and is an age-independent, average-stand-mortality model that predicts the development of fully stocked natural stands. An overview of the historical development and applications of DMD in forest management planning was given by Newton (1997). Smith and Woods (1997) developed a red pine (*Pinus resinosa*) DMD for Ontario (Figure 6-2). One example is provided below to illustrate sawlog production for red pine (Figure 6-2). Site index (SI) for each stand is estimated to be 20 cm. All estimates of stand density, volume production, and the timing of thinning and rotation harvests are given in Table 1 with an initial density of 1,200 sph (stems per hectare). To ensure that sawlogs reach a target DBHq (quadratic diameter at breast height) of 30 cm, the forest manager then drafts a line downward from the intersection of 30 cm DBHq isoline and the initiation line of mortality. Moreover, a line from the location of the commercial thinning (CT) is plotted, which runs parallel to the 18 m height isoline. This represents an age of 48 years (43 years breast-height age from site index curves, plus 5 years to breast height), and 575 sph are removed by thinning treatment. This results in an approximate extracted volume of 75 $m^3 \cdot ha^{-1}$ (or a basal area of 12 $m^2 \cdot ha^{-1}$). Consequently, the residual stand then has a density of 625 sph, and self-thinning will not start until individuals have attained a DBHq of 30 cm. The final harvest volume of sawlogs is calculated to be 469 $m^3 \cdot ha^{-1}$ (or a basal area of 44 $m^2 \cdot ha^{-1}$), and the total volume removed from the stand is estimated to be 544 $m^3 \cdot ha^{-1}$.

Table 6-1. Estimates for two thinning treatments for red pine stands (modified from Smith and Woods (1997) with permission). Age* assumes red pine (*Pinus resinosa*) will reach breast height (1.3 m) after five years. CT = Commerical Thinning; n/a = not applicable

	Sawlog production with commercial thinning
Initial density (sph)	1,200
Number trees cut at thinning	575
Total age at thinning (years)	48 (43 + 5)* for CT (based on height of 18 m on SI 20 curve)
Pulpwood volume at thinning (m3 ha–1) (pre-CT vol. – post-CT vol.)	75 [(1,200 sph × 0.26 $m^3 \cdot tree^{-1}$) – (625 sph × 0.38 $m^3 \cdot tree^{-1}$)]
Basal Area (BA) removed at thinning ($m^2 \cdot ha^{-1}$) (pre-CT BA – post-CT BA)	12 [(1,200 sph × (21 cm)2 × 0.00007854) – (625 sph × (24.5 cm)2 × 0.00007854]
Sawlog volume at rotation age ($m^3 \cdot ha^{-1}$)	469 (625 sph × 0.75 $m^3 \cdot tree^{-1}$)
Basal Area removed at sawlog rotation ($m^2 \cdot ha^{-1}$)	44 [625 sph × (30 cm)2 × 0.00007854]
Sawlog rotation age (years)	71 (66 + 5)* (based on height of 24 m on SI 20 curve)
Total volume harvested ($m^3 \cdot ha^{-1}$)	544 (75 + 469) (CT thinnings + small sawlogs)
Number trees cut at thinning	575
Total age at thinning (years)	48 (43 + 5)* for CT (based on height of 18 m on SI 20 curve)

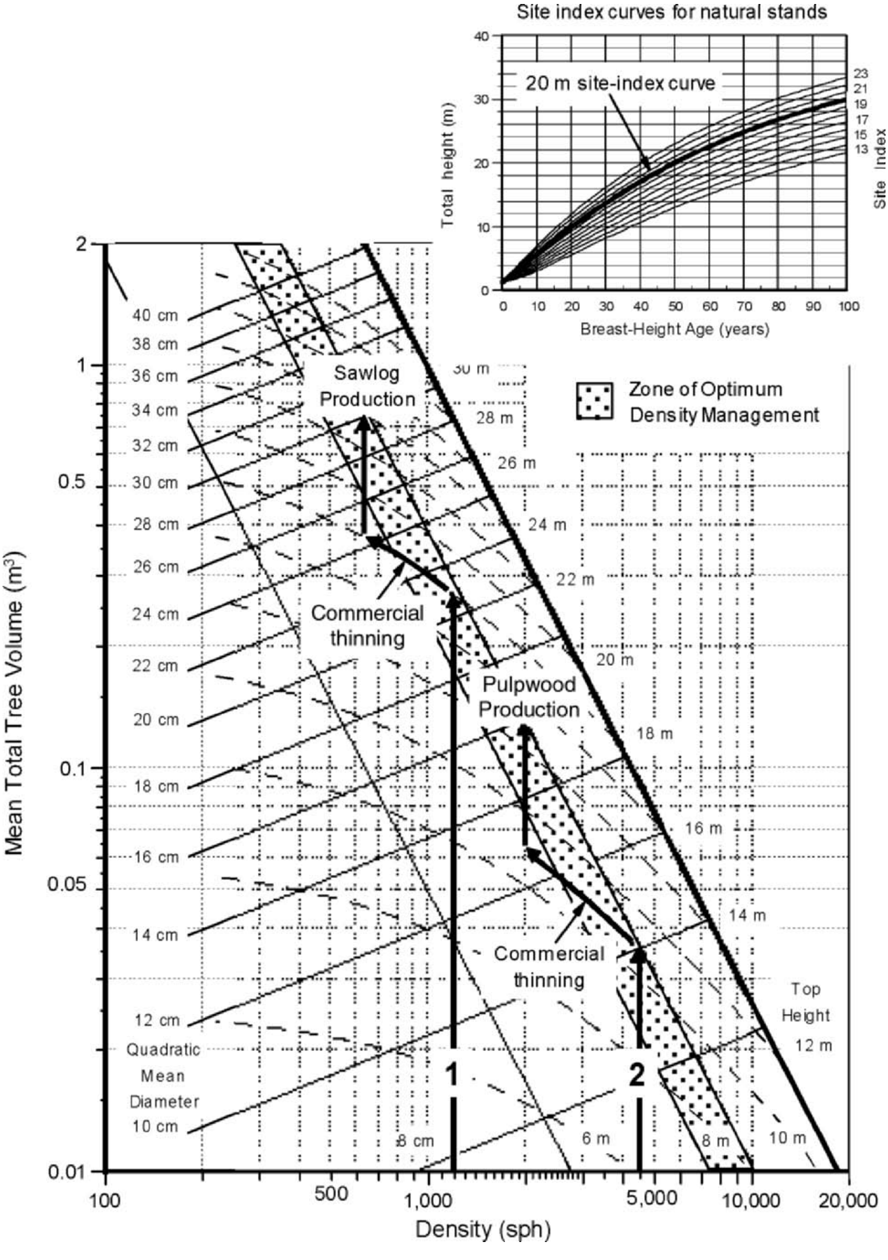

Figure 6-2. Stand development trajectories for red pine (*Pinus resinosa*) pulpwood and sawlog production (reprinted with permission from Smith and Woods 1997).

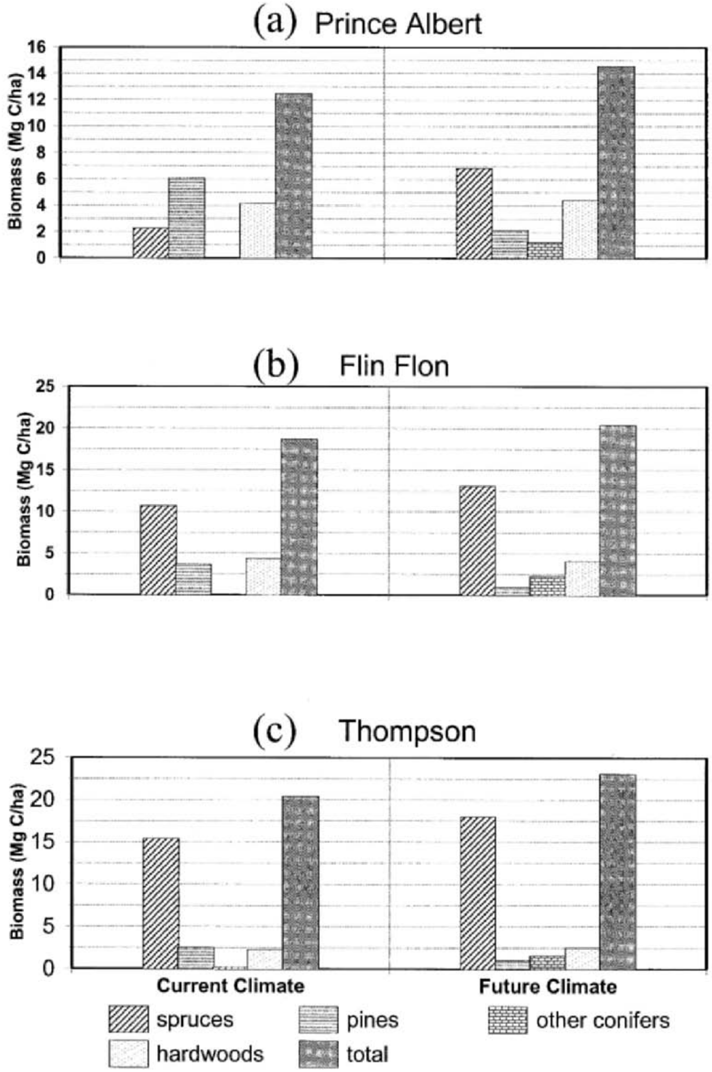

Figure 6-3. A comparison of boreal forest species composition and biomass, simulated by FORSKA 2.0, under (1) current climate and (2) future climate at (a) Prince Alberta, Saskatchewan (53°13'N, 105°41'W) (b) Flin Flon, Manitoba (54°46'N, 101°51'W) (c) Thompson, Manitoba (55°48'N, 97°42'W). Current climate is produced using data from the period 1884-1992 replayed to create a synthetic 1800-year time-series. The data presented for current climate are spatial average biomass (Mg C·ha^{-1}) averaged over the last 200 of the first 800 years of simulation. The data presented for future climate are spatial average biomass (Mg C·ha^{-1}) for the last 200 of the each 1800 years of simulation. Future climate is based on the Goddard Institute for Space Studies (GISS) general circulation model (GCM) under 2xCO$_2$ scenario (Hanson et al. 1988) (see Price et al. 1999b).

3.2 Case II: Simulating effects of climate change on species composition of boreal ecosystem using FORSKA 2.0

FORSKA 2.0 is a forest succession model originally developed to simulate landscape-level processes in Scandinavian boreal forests (Leemans and Prentice 1989, Prentice et al. 1993). Stand dynamics are simulated in arrays of 0.1-ha patches, interrupted at random intervals by patch-replacing disturbances. The representation of growth processes allows physiological parameters affecting photosynthesis to be specified, including the shape of light-response curve, and the ratio of intercellular to ambient CO_2 concentrations. FORSKA 2.0 also contains a simple soil-water-balance 'bucket' model that calculates average daily actual evapotranspiration using the Priestley-Taylor (1972) equation balanced against mean daily precipitation and soil-water storage. Soil moisture is then used as an environmental factor to limit sapling survival and tree-growth rates, instead of imposing a maximum temperature limitation to growth, as is used in the original succession models (e.g., Botkin et al. 1972, Shugart 1984). It has recently been used to investigate the potential impacts of climate-change scenarios on unmanaged boreal forest ecosystems in central Canada (Price and Apps 1996; Price et al. 1999a, b). Under the GISS (Goddard Institute for Space Studies) $2\times CO_2$ (doubling CO_2 concentration) climate scenario, significant shifts in species composition are predicted for all three forest sites, with pine and hardwoods contributing less to total biomass in the north (Thompson), but more in the south (Prince Albert) (Figure 6-3). In contrast, spruces and other conifers become more abundant in the north (Thompson), but less in the south (Prince Albert). Hardwood biomass is only mildly affected under GISS $2\times CO_2$ climate scenario, while spruces gain at all three locations, particularly in the south. Total biomass increased by about 13% in Thompson, 9% in Flin Flon, and 17% in Prince Albert.

3.3 Case III: Simulating effect of climate change and fire disturbances on carbon dynamics of boreal forests using CENTURY 4.0

CENTURY, as developed by Parton et al. (1987, 1993), is a general process model of plant-soil ecosystems that simulates the dynamics of C and N of various plant-soil systems including grassland, agriculture land, savannas and forests. It incorporates representations of key processes relating to carbon assimilation, turnover and decomposition, based on a set of existing submodels. It also permits simulation of many management measures, including grazing, cropping, fertilization, irrigation, and control of wildfire. The model has been described by Parton et al. (1987, 1993) and Metherell et al. (1993).

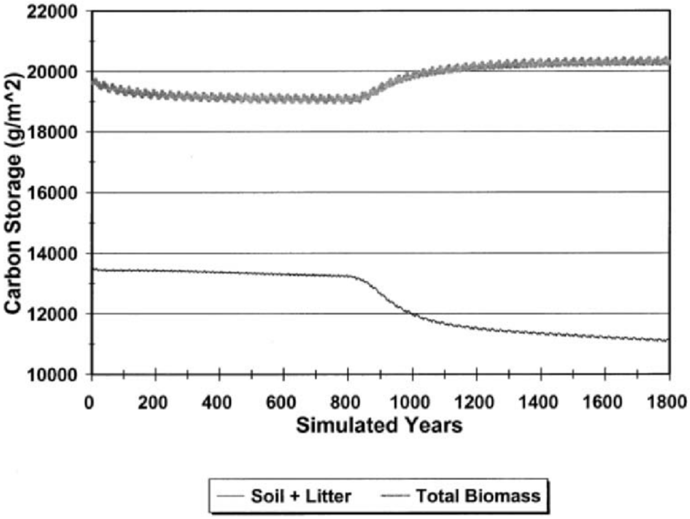

Figure 6-4. Total (above- and belowground) biomass, litter and soil-carbon density simulated by CENTURY 4.0 at Thompson, Manitoba (55°48' N, 97°52'W), using an average monthly climate record from the period 1958–1990. A simulated change in climate, derived from the GISS general circulation model (Hanson et al., 1988), was applied beginning at year 801, continuing until 900, followed by 800 years of a stable 2xCO_2 climate scenario without any ecosystem disturbances (from Peng and Apps, 1997).

The latest version, CENTURY 4.0, that operates on a monthly time step, also includes a water balance submodel, which calculates monthly evaporation, transpiration, water content of soil layers, snow-water content and, water flow between saturated soil layers. Major input variables for the model include (1) monthly mean maximum and minimum air temperature, (2) monthly precipitation, (3) soil texture, (4) atmospheric and soil N inputs, (5) plant lignin content, and (6) initial soil C and nutrient levels. Earlier versions of CENTURY were used widely to simulate plant productivity, biomass and soil C and N dynamics in agroecosystems (Paustian et al. 1992, Metherell 1992), grasslands (Parton et al. 1993, 1995, Hall et al. 1995, Xiao et al. 1995), tropical forests (Sanford et al. 1991, Vitousek et al. 1994,Townsend et al. 1995), as well as in savanna and tundra environments (Metherell et al. 1993). More recently, CENTURY 4.0 has been validated for boreal forest ecosystems in central Canada using field data of aboveground biomass and soil organic matter (Peng and Apps 1998, Peng et al. 1998, Price et al. 1999b). The potential impacts of climate change and fire disturbance on carbon dynamics of the boreal forest in the area of the Boreal Forest Transect Case Study in central Canada were reported by Peng and Apps (1998) and Peng et al. (1998). Under a GISS 2×CO_2 climate scenario the total biomass was slightly increased, and litter and soil carbon storage were greatly decreased due to increase in soil decomposition (Figure 6-4). An increase in fire frequency (from a 50- to a 150-year fire return interval) resulted in a decrease in total biomass (Figure 6-5).

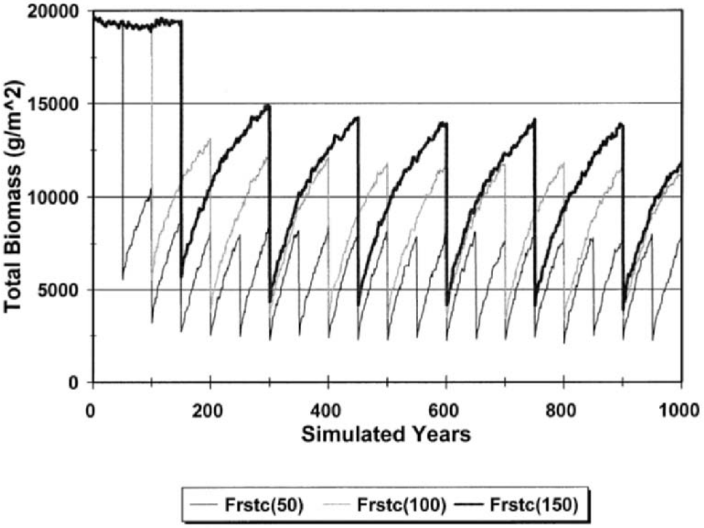

Figure 6-5. Sensitivity analysis of total biomass, simulated by CENTURY 4.0 using an average monthly climate record for 1958-1990, to changes in fire disturbance regimes at Flin Flon, Manitoba (54°46' N, 101°51'W). Frstc(50), Frstc(100), and Frstc(150) represent simulations with fire return intervals of 50, 100, and 150 years, respectively. (from Peng and Apps, 1997).

3.4 Case IV: Predicting forest growth and yield of boreal forests in Northern Ontario using TRIPLEX1.0

TRIPLEX 1.0 (Peng et al. 2002) is a generic hybrid simulation model of forest growth and carbon and nitrogen dynamics, developed and based on three well-established models: a forest production model of 3-PG (Landsberg and Waring 1997), a tree growth and yield model of TREEDYD3 (Bossel 1996) and a soil carbon and nitrogen model of CENTURY4.0 (Parton et al. 1993). The model is intended to be comprehensive without becoming complex, and minimizes the number of input parameters required, while capturing key processes and important interactions between the carbon and nitrogen cycles of forest ecosystems. It contains both empirical and mechanistic components so that it can be used for (1) making forest management decisions (e.g., growth and yield prediction), (2) quantifying forest carbon budgets, and (3) assessing the effects of climate change in both the short- and longterm. The structure of the TRIPLEX 1.0 includes four major components: (1) a forest-production submodel that estimates photosynthetically active radiation (PAR), gross primary productivity (GPP), and above-ground and below-ground biomass; (2) a soil-carbon and nitrogen submodel that simulates carbon and nitrogen dynamics in litter and soil pools; (3) a forest growth and yield submodel that calculates tree growth and yield variables (e.g., height, diameter, basal area, and volume); and (4) a simple soil-water-balance submodel that simulates water balance and dynamics. The simulation involves key processes and dynamics, including PAR, GPP, forest growth, biomass, soil carbon, soil nitrogen, and soil water. All simulations were conducted using a monthly time step, while output of simulations is summed yearly. TRIPLEX 1.0 is comprehensive without being complex, and minimizes the number of input parameters required. The input is relatively simple and mainly includes the location (latitude), climate, and some initial site conditions. Recently, TRIPLEX 1.0 has been successfully calibrated and tested for pure jack pine stands in Ontario (Peng et al. 2002, Liu et al. 2002) using 12 permanent sample plots measured by Kimberly Clark Limited between 1950 and the 1980s, and for major boreal tree species in central Canada (Zhou et al. 2004) using BOREAS field data. For example, Zhou et al. (2005) has used TRIPLEX 1.0 to predict forest growth and yield in the Lake Abitibi Model Forest (LAMF) in northeastern Ontario. The model was tested using field measurements, forest inventory data, and the normal yield table. The simulations of averaged tree height and diameter at breast height (DBH) showed good agreement with measurements for black spruce, jack pine and trembling aspen. The coefficients of determination (R^2) between simulated values and permanent-sample-plot (PSP) measurements were 0.92 for height and 0.95 for DBH. This study demonstrated the feasibility of testing and validating a hybrid carbon dynamic model using PSP measurements, and showed that the TRIPLEX 1.0 model can be used to provide growth and yield information to complement empirical growth and yield models for forest management practices. This approach is particularly valuable for areas where there are no or insufficient PSP data available.

4. CHALLENGES AND DIRECTIONS

4.1 Modeling ecosystem sustainability

There are two concepts embedded in the term, sustainability (CCFM 1997): sustainability of timber yield and sustainability of the ecosystem. Sustainability of timber yield refers to sustaining the production level of timber from the forest area. This implies maintenance of a forest, but not necessarily the original forest; sustainability of an ecosystem refers to sustaining the integrity of the natural forest in terms of its structure, function, composition (i.e., species composition and biological diversity), and ecological processes, along with the environmental services it provides.

One of the challenges and important issues regarding sustainable forest management is the question of sustainability, not only of timber harvesting, but of an entire ecosystem's structure and function (Christensen et al. 1996). Most traditional growth and yield models, which excluded soil processes and the role of ecosystem disturbance in determining ecosystem function, may be able to predict the continuity of timber harvest and the nature of future forest stands, but tell us little about the effects of timber harvesting on ecosystem structure and function. For example, the DMD (Smith and Woods 1997) allows forest managers to formulate reasonable consequences to various density manipulations by management objective, and provides a useful decision-support tool in stand-level management planning. However, with the increase of ability of DMDs to address multiple resource management objectives simultaneously (e.g., Strurtevant et al. 1996), the new generation of DMDs could play an increasingly important role in sustainable forest management (Netwton 1997, O'Hara and Valappil 1999, Newton, 2003). Forest succession models have been widely used by researchers and resource managers during the past three decades (Botkin et al. 1972, Botkin 1993). They have several limitations that restrict their application in investigations of long-term forest ecosystem sustainability. For example, an inadequate representation of the details and determinants of production ecology, the limiting role of soil and ecosystem disturbance processes (Kimmins 1996) are major limitations. Although FORSKA 2 (Prentice et al. 1993, Price et al. 1999a, b) addresses one of these limitations by incorporating fire disturbance in the simulation of forest species dynamics, it still lacks soil processes that impact ecosystem functions. Models such as FORCYTE (Kimmins 1990) and LINKAGES (Pastor and Post 1986) offer some insight into nutrient cycling and long–term productivity changes. New general models, such as FORECAST (Kimmins et al. 1999), TREEDYN3 (Bossel 1996), 3-PG (Landsberg and Waring 1997), and TRIPLEX 1.0 (Peng et al. 2002), which integrate empirical growth models with process-based ecosystem models, may provide more insight into sustainable forest management under changing environmental conditions. The greatest contributions of process models such as CENTURY 4.0 in sustainable forest management are that they are specifically developed for the purposes of investigating the response of ecosystem function (e.g., ecosystem productivity, carbon and nitrogen dynamics) to the long–term consequences of changes in climate and atmospheric CO_2 (Peng and Apps 1998, 1999), and to the effects of fire disturbances and harvesting regimes (Peng and Apps 1999, Peng et al. 20002, Jiang et al. 2002). However, CENTURY 4.0 is essentially a research tool, and has not been used to address questions of multi-purpose management of forest resources, which is indeed of interest to forest managers today.

4.2 Diversified forest modeling approaches

Traditional forestry objectives, aimed at managing for sustainable yield, are being replaced with those of sustainable ecosystem management (Kimmins 1997). This paradigm shift in forest management requires an effective transfer of results from researchers to forest managers. The key to forest ecosystem modeling for forest planning and management in the 21st century is the extent to which the ecosystem is treated holistically. Future growth and yield efforts will face the challenges of (1) including an increased number of silvicultural alternatives, (2) providing expanded information on tree quality and product yields, and (3) predicting long-term forest response to environmental stresses such as climate change, land use, and fire disturbance at landscape levels.

There is still a gap between forest ecology and applied forestry in developing and using forest simulation models. Foresters and forest managers prefer empirically or statistically based approaches. It has become fashionable among ecologists to favor mechanistic approaches over empirical ones (Bossel 1991, Battaglia and Sand 1998, Peng 2000). This increased interest in aspects of ecosystem dynamics led to the development of process-based models that perhaps were epitomized by the International Biological Program (Reichle 1981). The strength of process models is the weakness of the empirical models, and vice versa. The link between foresters and ecologists, coupled with combining empirical and mechanistic approaches into a hybrid approach, will certainly advance our understanding of the effects of future changing environment on sustainable forest management.

It should be noted that different purposes of application require different types of models, and different modeling approaches. For example, foresters, forest managers, and planners need forest simulation models that have more comprehensive description, such as planning tools for the development of forest management policy, and for assessing the long-term effects of forest practices and environmental pollution. Forest scientists, ecologists, teachers, and students require forest simulation models that have a more mechanistic explanation; for example, methods for studying forest succession dynamics, structure, and function, and models for predicting the response of future forests to changes in climate and atmospheric CO_2. Undoubtedly, there will not be a single model satisfying all of these diverse demands simultaneously. Only diversified forest modeling approaches can meet the demands of informing forest management decisions under the uncertainty of the future environment.

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Chapter 7

VISUALIZATION WITH SPATIAL DATA

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Abstract: Visualization has become a major tool in forest planning and management but it cannot be used alone. Advances in computer graphic capabilities and enhanced functionalities of Geographic Information Systems (GIS) have advanced the use of visualization beyond mapping. Visualization itself has become an effective tool for measuring and depicting impacts of management actions, and predicting responses of the forest to different forest operations or intervention strategies. It has been used to evaluate and forecast environmental change. With increased availability and accessibility to the public, it has also become a primary tool for capturing public perceptions through visual interpretations, and in communicating the effects of various management activities. The integration of visualization techniques and spatial data has advanced over the last few years and now constitutes a significant approach in general forest planning and decision making

Key words: 3D visualization; forest; management; landscape; data analysis; computer techniques.

1. INTRODUCTION

Visualization has become a practically useful technique over the last few years, and has been broadly applied in many areas. Visualization technology itself has also improved as a result of advances in the functionality and capabilities of computer hardware and software. Along with visualization, animation and 3D image modeling have also become popular partly because

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of advanced computer graphic capabilities, including enhanced display capabilities of geographic information systems (GIS). As the name implies, visualization is generally associated with computer-assisted procedures that visually present numerical data in a 'graphic' picture or display, from a simple graph of one dependent variable against one independent variable, to a virtual reality that enables a user to visually see the graphic representation of data.

McGaughey (1997a) stated that there are two general types of visualization particularly as they relate to forestry applications, namely, (1) scientific visualization - using analysis and graphing tools to classify, summarize, explore and present large data sets, and (2) virtual reality - using large data sets and rendering software to create 'virtual worlds' that can act as surrogates for the real world. The first type, sometimes referred to as data visualization, deals mainly with spatial data and the manner by which the results are represented and displayed, such as charts, diagrams, maps, and other graphics. These types of visualization can be useful in describing and explaining concepts, forest status or overall condition, and other ecological processes, which may not be well expressed in text or tabulated data. The second type is often the type that is most commonly associated with visualization. In particular, landscape visualization is often used for this type, which is used to represent site-specific and ground condition at varying degrees of realism. Bishop (1994), for example, strongly supports the use of 'virtual realism' as a visualization paradigm and communication tool, especially in dealing with environmental impacts due to management actions or human interventions in forestry and natural resource management. These visualizations often convey information on the expected future appearance of the landscape given certain conditions. Landscape visualization offers a graphic representation, including social implications of site-specific management interventions or scenarios, such as impacts on scenic beauty, recreations, and other cultural and property values (Sheppard and Salter 2004).

Visualization has been applied extensively in forestry and natural resource management. Much of the visualization work has been developed and integrated within a GIS platform. For example, McGaughey (1997a) provided a summary table describing the different software and the scale for which they were developed (See Table 7-1). Early visualization systems for forest management applications, as noted by Meitner et al. (2005), were useful, but generally quite abstract (Travis et al. 1975, Mykelstad and Wagar 1977). Later approaches, with advances in computer graphics, enhanced these earlier systems (e.g., Heasley 1990).

Table 7-1. Visualization techniques and software packages (updated from McGaughey 1997a)

Software Package Name	Visualization Technique	Scale	HW – OS	Cost	Additional Information Reference
Stand visualization system (SVS)	Geometric modeling	Plot	PC-DOS	Free	forsys.cfr.washington.edu/svs.html
UTOOLS and UVIEW	Geometric modeling	Stand or landscape	PC-DOS	Free	forsys.cfr.washington.edu/utools.html forsys.cfr.washington.edu/uview.html
SmartForest	Geometric modeling	Stand or landscape	UNIX (SGI or IBM-RS6000)	Free	www.imlab.uiuc.edu/SF/SF_II.html
Landscape management system (LMS)2	Geometric modeling	All scales	PC-Windows	Free	silvae.cfr.washington.edu/lms/lms.html
Gnu Image Manipulation Program (GIMP)	Video imaging	All scales	UNIX	Free	www.xcf.berkeley.edu/~gimp
USFS, Southern Research Station visualization system	Geometric modeling	Stand or landscape	UNIX	Free	so4702.usfs.auburn.edu/research/prob4/standviews.html
VistaPro3	Geometric modeling and image draping	Landscape	PC-DOS, PC-Windows, Macintosh	$$*	www.romt.com/Products/VISTA/index.html
Persistence of vision raytracer (POV-Ray)	Geometric modeling	All scales	Many platforms	Free	www.povray.org
VisualFX	Geometric modeling	Stand or landscape	PC-DOS	$$	Available from author: John Heasley
CLRview	Geometric modeling	Stand or landscape	Silicon Graphics IRIX	Free	www.clr.utoronto.ca/CLRVIEW/cvmain.html
Visual Explorer	Image draping and geometric modeling	Landscape	PC-Windows	Free $$	www.woolleysoft.co.uk
TruFlite	Image draping	Landscape	PC-Windows	Free $$	www.truflite.com
WCS and VNS	Image draping and geometric modeling	Stand or landscape	PC-Windows, Macintosh	$$$	www.3dnature.com
Ecomodeler/ Ecoviewer	Image draping and geometric modeling	Stand or landscape	PC-Windows, Macintosh	$$$$ Free	www.viewscape3d.com

*Commercial

Some current visualization systems have increased the degree of realism and representation validity of landscape visualization (Daniel and Meitner 2001). Modern data visualization systems have focused on data projections of future forest conditions, emphasizing traceable links between forest biophysical data and features (e.g., Daniel 1992, McGaughey 1998). Other applications of visualization in forestry include SmartForest (Orland, 1994), The Virtual Forest (Buckley et al. 1998), and more recently, EnVision, an environmental visualization system developed by the U.S. Forest Service (http://www.cfr.washington.edu/research.pfc/presentations/visualization/index.htm).

2. VISUALIZATION TECHNIQUES

McGaughey (1997a) identified four specific types of visualization techniques used in many software programs, namely, (1) geometric modeling, (2) video imaging, (3) geometric video imaging, and (4) image draping. Geometric modeling techniques build 3D models of features such as trees, ground surface, and plants, where each 3D object is assembled to generate a stand, forest, or landscape. Orland (1997) provides an example of an early application of this technique. Video imaging uses programs such as Adobe Photoshop allow cutting and pasting of digital photographic images to represent landscape changes. The technique is essentially a 2D approach that is difficult to link to objective data and model outputs (Tang and Bishop 2002). Geometric video imaging is a hybrid approach done within GIS by combining video imaging with geometric modeling. Hence, this approach is a combination of imagery and geometry.

Visualization in forestry can be done at three scales, namely, plot, stand, and landscape (Table 1). Different visualization tools and software are available for generating visualizations at different scales. For example, the Stand Visualization System or SVS (McGaughey 1997b), can be used at the stand level. SVS can generate 3D graphic images showing stand conditions represented by individual components such as trees, shrubs and others. Such images can be generated by SVS in response to silvicultural treatments and other forest management alternatives. One of the first landscape visualization tools was developed in SmartForest (Orland 1997). It is capable of incorporating large forest databases to represent the landscape. Other landscape visualizations include those developed by Orland et al. (1994), Bergren et al. (1998), Orland et al. (2001), and Sheppard (2004).

Among the three methods described above, perhaps the most commonly used is geometric modeling with 3D visualization techniques. One of the first applications of 3D visualization techniques was for visual impact assessment in natural resource management. 3D visualization is very much computer dependent. The quality of visualization, and the freedom of the user to access the visualization products, is closely related with the quality of the software and platform for visualization. A decade ago, one of the most important challenges to visualization technology was to provide the means to increase understanding of ecological processes through pictures, and to decrease the difficulty in producing visualizations (Helly et al. 1995). This difficulty, along with those described below, remains as an important challenge.

Currently available visualization software programs that have been used to visualize forested landscapes include the SVS (McGaughey, 1997a), UVIEW (McGaughey, 1997a) by the USDA Forest Service Pacific Northwest Research Station, Landscape Management System (LMS) (McCarter, 1997), SmartForest (Orland, 1994), World Builder by AnimaTek, SIMFOREST by Praxis Technical Group Inc., Ecomodeler and Ecoviewer by Viewscape3D Graphics Ltd., and ArcView 3D Analyst and ArcScene by ESRI. Most of these programs were designed to be used at specific scales, and are not readily adaptable to other scales. For example, SVS is used at the stand scale, while UVIEW, SmartForest, and SIMFOREST are designed for use at the landscape scale. Some programs use simple geometric shapes, such as cones and cylinders, or unrealistic tree designs to represent tree species (e.g., LMS, SVS, UVIEW, and SmartForest), while others are only for aesthetic purposes, and cannot be used with actual spatial information. A few programs, such as ArcScene, treat 3D trees as part of the terrain vectors and are prohibitively resource-intensive for high-quality close-up views. World Construction Set (WCS, 3D nature, LLC. 2002), Visual Natural Studio (VNS) and Scene Express (SE, 3D nature, LLC. 2002) by 3D Nature are among the best insofar as they can be used at all scales, use real spatial information, and create realistic, natural-looking features. Disadvantages of these visualization technologies include the remand of computation and graphical power for hardware, and the lack of interaction between users and the visualization products, which lead to another challenge: the real-time interaction.

3. CONTEMPORARY 3D VISUALIZATION

3D visualization of forest landscapes can be used to visualize stand succession, landscape transformation, and regional planning, and to improve decision-making processes and understanding of forest management in general (Karjalainen and Tyvainen 2002). 3D visualization provides an alternative way to “access” to forests of interest. 3D visualization can display forest changes over time, including changes caused by management activities and disturbances, and it can also demonstrate future development, based on existing data and modeling. Results from Wang et al. (2006) illustrate that 3D visualization is a promising tool that has yet to be fully appreciated for its potential to improve management of forest resources. This potential is especially critical when aesthetic values are emphasized, such as regional planning for a tourism destination, or harvesting activities on a forest in close proximity to urban or high traffic areas. Nevertheless, ecological values do not always agree with aesthetic values in forest planning or forest design. However, using 3D visualization technology enables resource managers to more effectively consider both ecological values and aesthetic values.

Because of interactions between management activities and unpredictable natural disturbances, there is normally uncertainty about the future of any forest landscape (Bell 2001). Persuasive images presented by visualizations sometimes may be misleading, giving people a false sense of confidence (Bell 2001). For instance, when creating a visualization using a still snapshot, one might unintentionally choose to display the more aesthetically pleasing aspects of the forest, which may unduly bias perceptions of users. This bias could be minimized by using animations that fly through, or zoom in and out of, the scene.

Visualizing the current forest is relatively easy with the help of remote-sensing technology, possibly combined with field surveys. However, visualization of both future and historic conditions is more problematic. When visualizing future changes within a forest, for example, reliable simulation of forest growth is essential for creating reliable visualizations. Conversely, visualizing the history of the forest is difficult unless adequate historical data are available.

4. VISUALIZATION IN FOREST PLANNING

4.1 Application areas of visualization tools

Orland (1994) provides an excellent overview of visualization techniques and how they are incorporated in forest planning. Daniel (1992) described the use of data visualization as decision support for environmental management. Bishop and Karadaglis (1997) described how visualization combined with GIS and modeling can be used in natural resource management. A special issue of the journal, *Landscape and Urban Planning*, reported on a number of applications of data visualization such as: evaluating regional changes based on local expectations (Orland 1992), applications of visualization in the U.S. Environmental Protection Agency (Culati et al. 1992), and the U.S. soil conservation Service (Wells et al. 1992). Other studies and applications describing the use of visualizations include: predicting the visual effect of forest operations (Bergen et al. 1995, Heasley 1990, McGaughey 1998), predicting human response to future environments (Daniel and Meitner, 1997), predicting scenic beauty (Bishop and Hulse 1994, Daniel 1997), pest management (Lynch and Twery 1992), growth and yield (McCarter 1997), and forest growth and landscape changes (Thuresson et al. 1996).

4.2 Spatial data and visualization

Lessons learned and experiences gained from applications discussed in Section 4.1 show that data analysis and visualization are effective tools, particularly for communicating forest conditions or futuristic forest scenarios in response to different management actions. However, Meitner et al. (2003) noted that, although much progress has been made on forest visualization, there is still great potential for improvement, particularly in the use of visualization for exploring and forecasting alternative ecosystem management scenarios. Subsequently, Meitner et al. (2005) indicated that "new data-driven and increasingly automated visualization of forest management scenarios are now becoming feasible, and offer some advantages in conveying complex spatio-temporal alternatives." Several authors have recognized the enormous promise of visualization, particularly its potential beyond mapping or as a communication tool, but more importantly as a significant component of a decision-support system (Meitner et al. 2005, Sheppard 2000, Meitner and Gandy 2004, Bishop and Kardaglis 1997).

The potential to enhance the capabilities of visualization beyond simple graphical representations was noted by Bishop and Karadaglis (1997), who proposed linking visualization approaches with modeling to more fully capture natural resource management, which typically requires prediction of environmental change over time and on large areas. They argued that, by combining GIS-based environmental modeling and visualization, complex decisions can be assisted by effective presentation of the outcomes of systems modeling (Bishop and Karadaglis 1996, Tang and Bishop 2002).

The value of integrating visualization systems with modeling systems as part of a multi-disciplinary approach to forest-management planning and decision making is now widely recognized. Tang and Bishop (2002) stated that the "trend for spatial decision support system development is the integration of GIS, modeling and visualization," and presented different integration methodologies including their degrees of interactivity, and levels of integration. They concluded that the ideal forest-management system should posses the analytical functions of GIS, prediction capabilities of models, and realistic visualization of the forest. A special issue of the journal, *Landscape and Urban Planning*, addresses potentials and advances in combining modeling, analysis, and visualization. In their editorial, Lange and Bishop (2001) concluded that, while there are advanced tools for simulating and visualizing landscape change, measuring visual preferences, monitoring and modeling environmental behavior, few consider the application of virtual reality, artificial intelligence, and integrated decision-support systems. Gimblett et al. (2001) describe a possible design for a simulation system that integrates statistical analysis, simulation, and visualization with computer modeling to analyze complex human-environment interactions. Their study is one of the first to explore procedures for representing the human decision-making process, behavioral patterns, and associated impacts within a dynamic human-environment interaction. They stated that this simulation system must provide

> "opportunities to: (1) develop methods to extract human behavior and physical systems data, rules that define how individuals communicate and interact with each other and their environment, (2) develop automated techniques for statistically comparing actual human-environment interactions and associated impacts with simulated outcomes, and (3) the use of visualization methods for evaluating simulation outcomes against actual human-environment interactions."

Sheppard (2001) further argued for the need to have guidance or a code of ethics for land visualization, in part because of the risks associated with the growing but unstructured use of visualization, particularly as a public communications tool in forest planning.

Following the idea of integrating visualization and modeling, particularly in the context of decision-support systems, Sheppard and Meitner (2005) combined visualization with Multi-Criteria Analysis (MCA). This study perhaps exemplified the integration concept at its fullest, because it combined model-based expert evaluations of alternative forest scenarios that were depicted using realistic 3D landscape visualization under a participatory planning and decision-making environment, implemented using MCA. The study focused on combining participatory decision making in the specific context of sustainable forest management. The study concluded that,

> "if participatory decision support is to be effective in sustainable forest management, we will need integrated approaches … applying techniques such as public Multi-Criteria Analysis and supporting tools [i.e., GIS and

> visualization] to help bridge the gap between general participatory processes and complex decision support systems."

5. EXAMPLES OF VISUALIZATION

In this section, we describe some of the principles of visualization using data obtained from different sources. The first step in 3D visualization was to create realistic tree images for forested ecosystems, a crucial component for high-quality visualizations. The individual tree images were generated from two sources: (a) field photographs of individual trees that were edited using advanced photo-editing techniques, and (b) tree images designed in a graphics software package, such as TreeProfessional (Onyx Computing Inc. 1997). For each species, several samples were needed to represent the ages and forms of trees of this species. We took pictures of trees growing under closed canopy conditions to most accurately represent natural forest ecosystems.

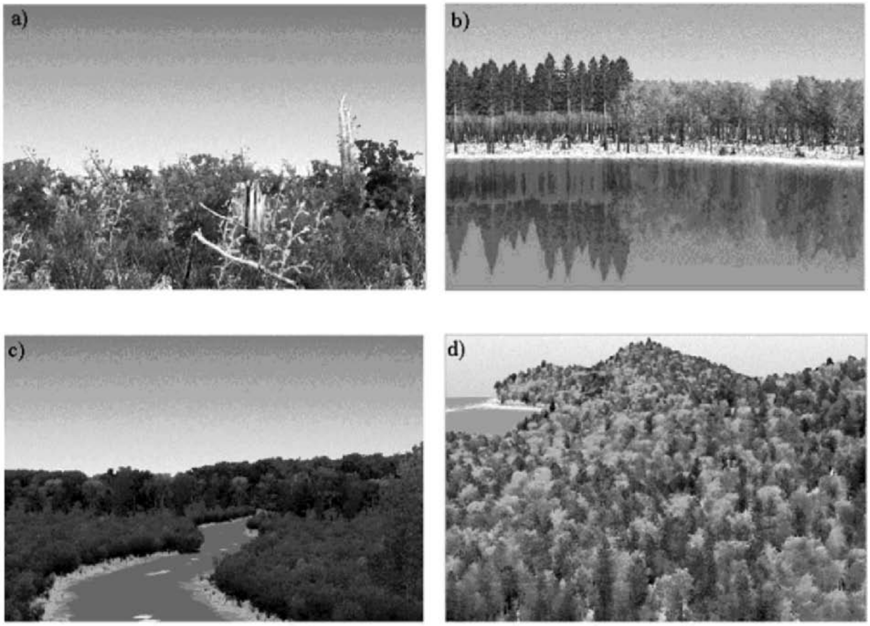

Figure 7-1. Examples of visualization capability: a) objects other than trees in forest, such as snags, stumps, logs, herbs, and shrubs, b) lake, c) road, and d) topography.

3D visualization can provide more information than GIS maps with different tree forms and tree heights (Figure 7-2a vs. b) (Plate 7-2). In GIS maps, forest types A, B, C, and D were differentiated by different colors (Figure 7-2a) (Plate 7-2), while in 3D visualization they were differentiated by forest structure and age based on unique tree images and realistic tree heights for each stand (corresponding forest patches of A, B, C, and D in Figure 7-2b) (Plate 7-2). Differences between regenerating stands and mature stands become visible on the 3D visualization because additional information, such as tree height, stand density, and species composition, etc., can be represented for each stand during visualization.

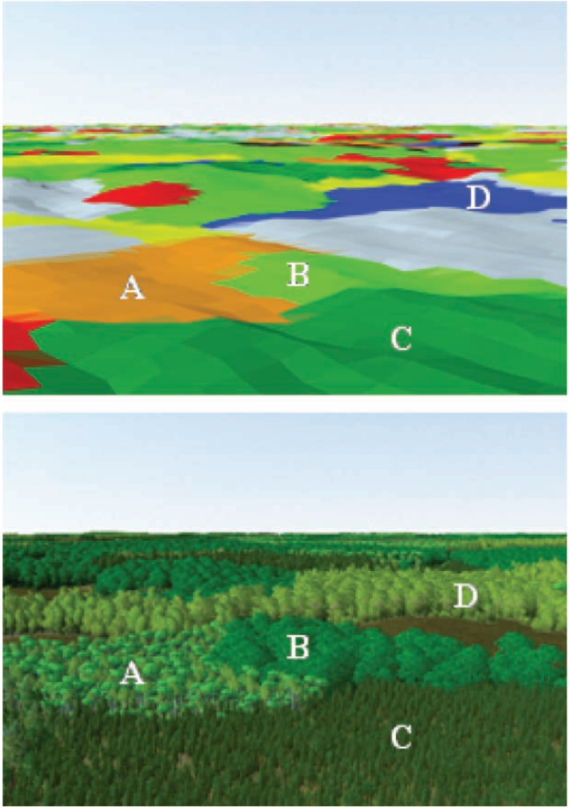

Figure 7-2. An example of visualization based on existing vegetation data: a (top) is a GIS map draped over the terrain; b (bottom) is 3D visualization of the exact area as in a. A, B, C, and D represent forest stands of bigtooth aspen, northern red oak, red pine, and paper birch, respectively. (See also color plate 7-2 on p. CP9)

The second step was to develop GIS layers of different forest and land types from forest inventory sources, and a digital elevation model (DEM) for topography. The forest and land cover was subsequently draped over the DEM. Data on tree composition also was needed for various trees of different species to place within the cover types.

Visual Nature Studio (3D Nature 2002) was used to integrate all information and generate a 3D virtual forest. The flexibility of this software allowed users to visualize forests from within-stand to landscape levels. The ecosystem design capability in Visual Nature Studio allowed the terrain to be covered with rock, soil, and foliage based on the natural sequence of ground, understory, and overstory layers. Different ecosystems were assigned according to site-specific tree-species composition, sizes and densities for both understory and overstory vegetation. The realism of this approach was maximized by including non-tree objects and other stand and landscape features, such as shrubs, herbs, snags, logs, stumps (Figure 7-1a), a lake (Figure 7-1b), a road (Figure 7-1c), and an overall topographic view (Figure 7-1d).

Combining real images of trees and ecosystem information with management practices, we can create realistic visual scenarios of forest management (Figure 7-3). Two different management effects were examined. Three different scenarios in an aspen forest were visualized: before any management (Figure 7-3a), residual cutting (i.e., some trees of certain species were left in a stand during the cutting, Figure 7-3b), and clearcutting (i.e., all trees were removed, Figure 7-3c).

3D visualization also is useful to visualize changes in forest conditions based on historical aerial photography. Such a technique worked well for examining the effect of a hurricane on the Hobcaw Forest in Georgetown County, South Carolina (Figure 7-4). Data for this reconstruction were obtained from 1:12,000 color infrared aerial photographs taken in February 1976 and 1990 (the Hurricane Hugo occurred in 1989). We determined a height for each diameter class. Diameter was estimated from the regression of diameter on crown perimeter. Height was estimated from regression of height on diameter. A DEM was developed for the area of interest from leveling information collected during a 1986 study of the stands in this area. This DEM formed the base for the rendered forest. Likewise, the position of the road was digitized from the rectified photograph. Realistic-looking trees were created using the TREE_PRO software. With this software, we created between three and five renderings of each species to be associated with different subranges of diameter distribution. This allowed small trees to appear considerably different from larger trees. Because the stand had been repeatedly burned, understory was restricted to the edges of hardwood areas. We added a ground color similar to fresh pine needles, and a grass similar to young switch cane. The stand was heavily damaged by Hurricane Hugo in 1989, because of which, there were quite a few dead trees afterwards. Using

3D visualization, we can compare the forest from point to point, before- and after-Hugo (Figure 7-4). Understanding the impact of the hurricane can be greatly enhanced by the ability to reproduce the essential visual qualities of the previous stand.

Figure 7-3. Visualization on different cutting alternatives of an aspen forest. The left column is a view forest edge and the right column is a new inside a forest. There are three cutting alternatives: no cutting (top), residual cutting (middle), and clearcutting (bottom).

The same technique can be used for visualizing effects of fire and other disturbances. Moreover, this approach is effective in comparing current and projected forested landscapes. Future forests also can be rendered as 3D views on a computer screen when growth models are used to create scientifically valid representations of forest conditions. It is even possible to represent centuries-long visions of the forest to the general public. Historical aerial photographs can provide views of an entire forest, and reflect the size and spatial distribution of trees at that point in time. We used remote sensing and GIS techniques to semi-automatically identify tree crowns (Williams et al. 2004). Stand records can then be used to correlate actual tree sizes to relative size information provided by aerial photographs. With this data, we can produce visualizations with realistic trees of the same species, size, and position of those in the actual forest at the time of the photograph.

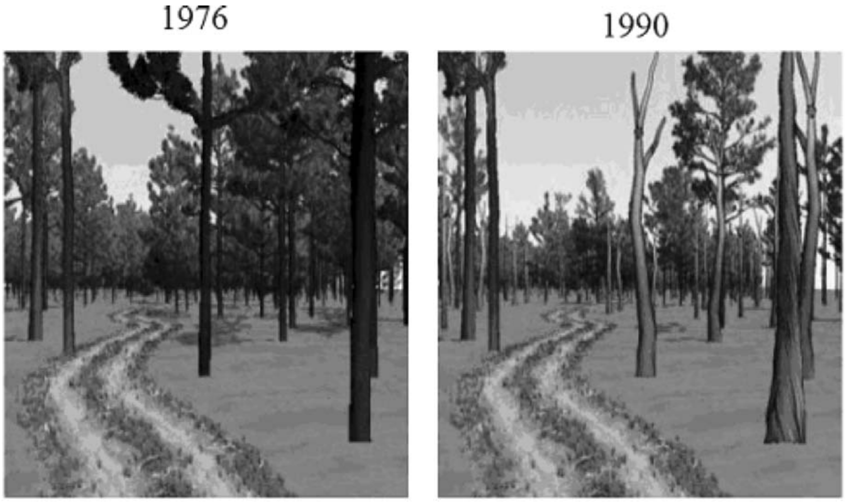

Figure 7-4. Comparing the forest before and after Hurricane Hugo in 1989 using 3D visualization.

6. CONCLUDING REMARKS

This chapter describes the principles of visualization techniques, and their application to forestry and natural resource management. We have also provided an overview of the different state-of-the-art techniques, particularly those that deal with linking or integrating visualization with other modeling techniques. Such integration extends the use of visualization beyond simple graphic display and into the realm of general planning and decision making. Integration of visualization systems with other modeling tools creates an integrated decision-support system that combines the analytical capabilities of models like GIS, the prediction and simulation capabilities of other modeling tools like MCA, with the realistic graphical display capabilities of visualization. These capabilities greatly enhance the use and scope of application of visualization technologies.

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Chapter 8

COMPUTER-AIDED DECISION MAKING*

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Abstract: Several major classes of software technologies have been used in decision making for forest management applications over the past few decades. These computer-based technologies include optimization, expert systems, network models, multi-criteria decision making, and integrated systems. Each technology possesses unique advantages and disadvantages, and has been applied differentially to decision making in forestry. Several example DSS highlight the incorporation of these various technologies for vastly different management problems. Likely future development trends for decision support technologies over the next few decades include: Internet implementations, agent-based applications, increased social science components, and participatory decision making. As with most other computer applications, in general, we expect that decision support will transition to ever smaller devices that will take advantage of ubiquitous computing.

Key words: Decision support; decision making; optimization; expert systems; networks; multi-criteria decision models; integrated systems.

1. INTRODUCTION

Almost 30 years ago, Mintzberg et al. (1976) proposed a general model for the decision-making process (Figure 8-1). The Mintzberg model has stood the test of time; it is still widely accepted today as a general description of the multiple alternative processes and pathways that individuals and organizations use to get from problem recognition to problem resolution, which culminates in some course of action. Any software system that

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explicitly assists with the implementation of one or more components of the overall process can be described as a decision-support system (DSS). Holsapple (2003, p. 551) nicely captures the essential features of a DSS as:

> A computer-based system composed of a language system, presentation system, knowledge system, and problem-processing system whose collective purpose is the support of decision-making activities.

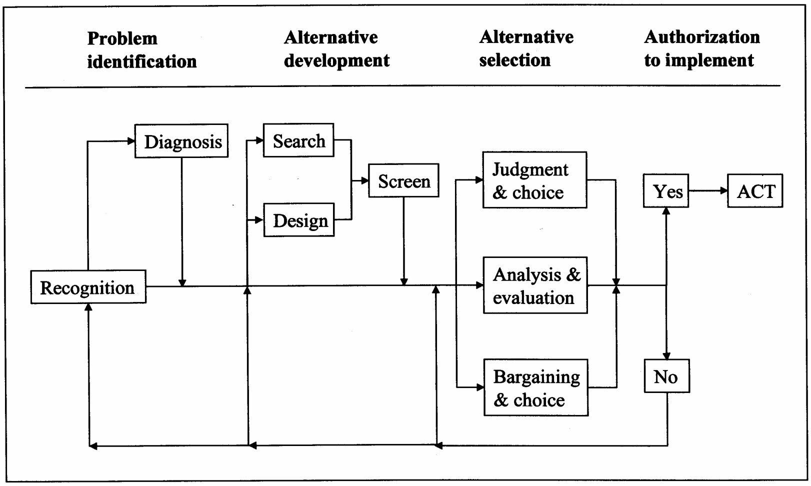

Figure 8-1. The Mintzberg planning process (Mintzberg et al., 1976), after Rauscher (1999). The Mintzberg process presents a general approach to planning, representing all, or at least most of, the classic variations on any planning process. Planning proceeds through the four steps of problem identification, alternative development, alternative selection, and a final decision to either implement the selected alternative, or cycle back to one of the first three steps. In each of the first three steps, multiple pathways are possible.

Two key attributes in the Holsapple definition are a subsystem for processing problems and purposeful support of a decision-making process. Many DSS focus exclusively, or nearly so, on the alternative-selection phase of the overall process (Figure 8-1). Some examples of systems that conform to the Mintzberg and Holsapple definitions and that usually focus on the alternative-selection phase include optimization systems, expert (or knowledge-based) systems that provide a framework for applying procedural or reasoning knowledge to decision problems, neural networks, Bayesian belief networks, and multi-criteria decision making, e.g., the analytic hierarchy process.

This chapter provides an introduction to DSS technologies as they have been applied to decision making in forest management. In terms of the underlying theories and technologies, the breadth and depth of this subject are enormous. Several to many volumes typically have been devoted to each of the topics covered in the following sections. So, we make no pretense to a comprehensive treatment of the subject. Instead, this chapter is intended to serve more as a roadmap for students of digital technologies with an interest in decision making, by suggesting approaches that may be worth investigating further.

In the following sections, we begin by looking at the origins of DSS, review several of the contemporary technologies including a few notable examples from forest management that demonstrate more comprehensive approaches to decision support, and speculate a little on the direction in which DSS development for forest management is likely to head in the near future.

2. MATHEMATICAL PROGRAMMING

Perhaps the earliest form of DSS to achieve widespread use in forest management was an approach based on optimization. The Forest Planning (FORPLAN[10]) system was developed by Johnson (1980, 1987), and was the primary analytical system used in strategic planning for national forests in the United States throughout the 1980s and into the early 1990s (Iverson and Alston 1986). The basic objective of any FORPLAN model is to optimize resource allocation and scheduling on a management area within a specified time frame, given well defined management objectives and constraints.

Use of mathematical programming as a basic tool for strategic forest planning has declined somewhat in the United States since the 1980s, in part because the black-box solutions of such systems pose a liability for resource management agencies (Gustafson et al. 2003). In particular, the difficulty of explaining the derivations of FORPLAN solutions was perhaps the most problematic issue (O'Toole 1983), given enormous public interest in the management implications of model solutions. Nevertheless, mathematical programming remains a popular and viable approach to decision support for strategic planning as evidenced by the continued use of the Spectrum system (http://www.fs.fed.us/institute/planning_center/plan_spectrum.html), a later evolution of FORPLAN, now maintained by the U.S. Department of

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[10] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Agriculture, Forest Service. Key attributes of Spectrum (anonymous) include:

- Multi-resource modeling. The system provides a generic framework for modeling any resource. A basic configuration depends on user-defined analysis units, management actions, activities and outputs, resource coefficients, and economic information.
- Spatial and temporal scales. Spectrum applications are not scale-specific. Up to 90 time periods of any length may be used to support analysis at relevant spatial and temporal scales.
- Multiple options for mathematical programming. Spectrum supports numerous combinations of optimization techniques and objective functions. Optimization techniques include:
  - Linear programming (optimization of a single criterion).
  - Mixed-integer programming (optimization with categorical outcomes).
  - Multi-objective goal programming (simultaneous optimization of multiple goals).
  - Stochastic programming to account for random events such as fires, pest epidemics, and uncertainty about data.
- Specifications for objective functions. Options for objective functions in traditional linear programming include maximizing or minimizing a single outcome or measure of performance. Objective functions for goal programming include minimizing under-achievement of goals, minimizing over-achievement of goals beyond thresholds, or minimizing both. Two additional options for objective functions are MAX/MIN (maximizing the minimum level of occurrence for a critical resource) and MIN/MAX (minimizing the highest level of occurrence of an undesirable outcome).
- Simulation of ecological processes and modeling natural disturbance. Spectrum allows embedding simulation of ecological processes and modeling of natural disturbances by means of state, flow, and accessory variables in dynamic equations.

The Regional Ecosystems and Land Management (RELM) system extends the utility of Spectrum solutions by apportioning forest-wide, strategic planning solutions to tactical sub-units of the forest such as watersheds (http://www.fs.fed.us/institute/planning_center/plan_relm.html). Cumulative effects and connected actions can be analyzed both within and between sub-units, allowing planners to evaluate how alternative management scenarios affect neighboring units.

3. EXPERT SYSTEMS

Expert systems operate on knowledge to solve problems in a manner somewhat analogous to human reasoning, based on concepts and principles from artificial intelligence (Jackson 1990, Waterman 1986). Typical applications of expert systems include diagnosis, classification, and prediction. They have evolved as a class of DSS technology to deal with problems not otherwise readily amenable to conventional computational solutions such as optimization, simulation, and statistical methods. The essential components of all such systems are a set of facts and rules (collectively, a knowledge base), an inference engine that interprets and schedules execution of rules, and one or more interfaces for the development and execution of an application (Figure 8-2). One of the more attractive features of these kinds of systems is that nearly all provide some form of explanation facility that helps a system user understand the derivation of solutions.

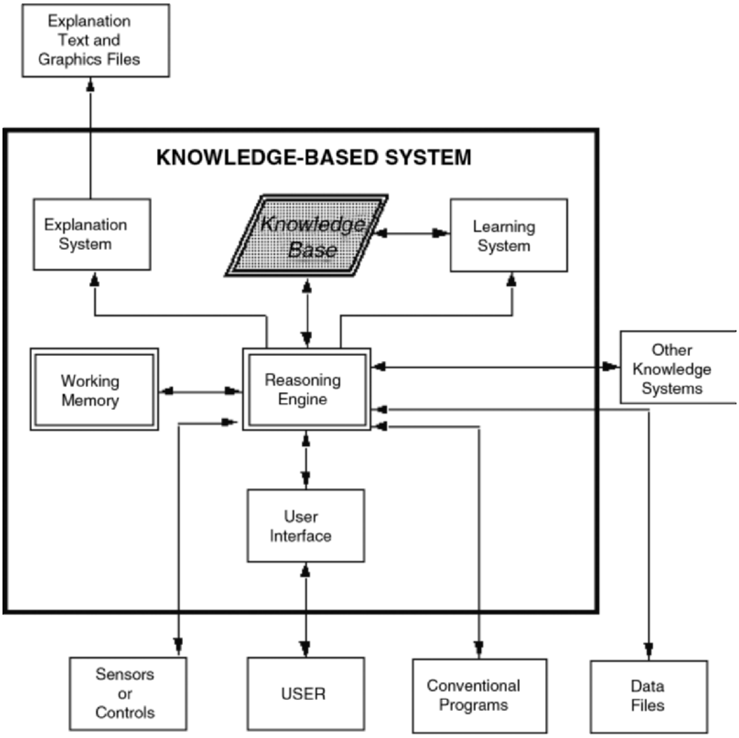

Figure 8-2. Basic components of an expert (or knowledge-based) system (Rauscher and Reynolds 2003).

MYCIN (Buchanan and Shortliffe 1984) is an early example, and still one of the most famous examples, of an expert system that was designed to provide medical diagnoses. The C Language Integrated Production System (CLIPS) was one of the earliest expert system development environments, and was developed at the Johnson Space Center of the National Aeronautics and Space Administration, beginning in 1984. CLIPS continued to evolve over the years (Giarratano and Riley 1998), is still widely used, and is available through the public domain (http://www.ghg.net/clips/CLIPS.html).

Expert system applications in forestry began appearing in the late 1980s (Schmoldt and Martin 1986). Some examples include a diagnostic and risk assessment tool (Schmoldt 1987, Schmoldt and Martin 1989) for insect and disease outbreaks in red pine (*Pinus resinosa*), an advisory system providing stand prescriptions for deer and grouse (Buech et al. 1989), a silvicultural system for managing red pine plantations (Rauscher et al. 1990), and a system for diagnosing the hazard and risk of bark beetle outbreaks in Alaska (Reynolds and Holsten 1997). Numerous other expert systems were developed to assist with forest pest management, silvicultural prescriptions, and timber harvesting, among other things (Durkin 1993). Developed initially as stand-alone software, eventually expert systems were integrated with optimization, simulation, geographic information systems (GIS), and other technologies covered elsewhere in this text.

4. NETWORK-BASED MODELS

Network theory has produced several successful approaches to representing problem-solving knowledge as a means of delivering decision support. Three of the more successful, and which are in relatively common use today, include artificial neural networks (ANN), Bayesian belief networks, and logic networks, each of which is described in the following sections. All three of these network-based systems have their roots in artificial intelligence, and, like expert systems, are well suited to applications such as diagnosis, classification, and prediction although each has particular strengths as discussed subsequently. Expert systems are often referred to more generically as *knowledge-based systems*, and this term applies equally well to Bayesian belief networks, and logic networks, so we will use this term hereafter as more preferable on both practical and epistemological grounds (it is not always easy to define what constitutes expertise, and it may even be regarded as a matter of opinion).

4.1 Artificial neural networks

System designs for ANN (Figure 8-3) were inspired by neuroscience and its understanding of the biological neuron (Wasserman 1989). Although common uses of ANN include diagnosis, classification, and prediction as already mentioned, perhaps their greatest potential is the general area of pattern recognition, e.g., Schmoldt et al. (1997) (that is, a form of classification, Turban and Aronson 1998, Zhang 2000). Notable examples of ANN development systems include Brainmaker (http://www.calsci.com) and Alyuda (http://www.alyuda.com), but many other systems exist (see, for example, http://www.it.uom.gr/pdp/DigitalLib/Neural/Neu_soft.htm).

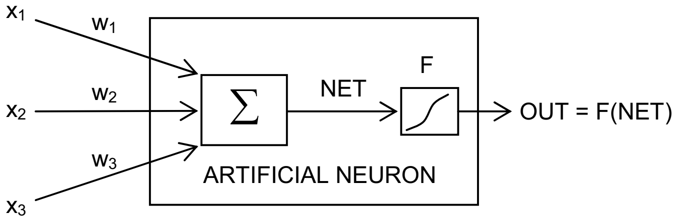

Figure 8-3. The basic architecture of an artificial neuron, after Wasserman (1989). Artificial neural networks are typically composed of two or more layers of such neurons.

One of the more interesting aspects of these types of systems is their demonstrated potential for learning, generalization, and abstraction (Wasserman 1989), in some respects fulfilling some of the early expectations for expert systems (q.v., Feigenbaum 1977, Winston 1977, Duda and Gaschnig 1981) that never really materialized. On the other hand, as Wasserman also notes, ANN are not a panacea. They can make mistakes, training procedures can produce suboptimal results or may fail to converge to a solution at all, and determining an optimal network design can be difficult. Moreover, like optimization systems, ANN have the same *black box* liability: they may produce reliable, accurate results, but there is no good intuitive explanation for their results that can be readily derived from the network structure itself.

ANN have been applied in a variety of contexts for forest management, including prediction of forest cover type (Blackard and Dean 1999), classification of ecological habitats (Liu et al. 2003), and detection of forest fires (Arrue et al. 2000). Notice that each of these applications is an example of pattern recognition in the broad sense. For these very technical and highly specific applications, lack of explanation facilities might not be viewed as a significant liability. Peng and Wen (1999) and Schmoldt (2001) review several additional applications in forest management.

4.2 Bayesian belief networks

Bayesian belief networks (or simply Bayesian networks hereafter) make use of Bayes' theorem from probability theory to model the likelihood of events by explicitly representing conditional dependencies between variables of a problem domain (Pearl 1988). Not surprisingly, Bayesian networks find their most natural application in prediction, because the inference process derives from the likelihood of events. A Bayesian network encodes assertions of conditional independence in a directed acyclic graph that provides an intuitive graphical representation of the relevant knowledge, including interactions among the various sources of uncertainty (Howard and Matheson 1981). Netica (http://www.norsys.com/index.html) is perhaps the most well known development system for design of Bayesian networks, but a number of such systems are available (see, for example, http://powerlips.ece.utexas.edu/~joonoo/Bayes_Net/bayes.html#belief).

A significant claim for Bayesian networks is that they provide a parsimonious representation of conditionality among variables that makes it practical to model real-world problems more effectively than methods for determining causal relationships based on more traditional probability theory (Pearl 1988). For example, independence among variables is easy to recognize in the graph representation employed by most development systems, and conditional dependencies can be easily recognized in the directed graph. As a result, a model based on a Bayesian network need not consider all possible joint probabilities, and extraneous pathways can be ignored. A uniquely powerful feature of Bayesian networks is that even though causation in these graphs is unidirectional, Bayes' theorem allows us to reason backwards from events to evidence.

Ellison (1996) described an interesting application of Bayesian networks to directly support the adaptive management process (Holling 1978, Walters 1986):

> Adaptive management is precisely analogous to an iterative Bayesian learning and decision process. Prior information is specified, decisions are made, and consequences are observed. The consequences are treated not as final events, but as new sources of information (new prior probability functions) for subsequent "experiments" (events, likelihood functions) that lead to modifications in management practices (new decisions).

Although Bayesian inference has been used very successfully in ecological research, it has not been widely adopted to date by resource managers as an approach to decision making (Ellison 2004). Lack of application in this context has been attributed, among other things, to "requirements for precise quantification of management options and their associated utilities or outcomes" (Ellison 2004). Perhaps, decision analysts and researchers need to work more closely with managers to develop useful applications of Bayesian networks.

4.3 Fuzzy logic networks

In the early years of knowledge-based system development, prevailing conventional wisdom held that such systems were best suited for very narrow, well defined problems (Waterman 1986). This is clearly reflected in the catalog of systems documented by Durkin (1993). However, the integration of fuzzy logic (Zadeh 1975a, 1975b, 1976) into knowledge-based systems in the early 1990s, as exemplified in systems such as a fuzzy version of CLIPS (Giarratano and Riley 1998) and NetWeaver (Miller and Saunders 2002) opened up new possibilities for applying knowledge-based methods. This marriage of technologies permitted application to much more general and abstract kinds of problems related to the management of natural resources, in general, and forest management in particular (Reynolds 2001a, 2001b).

Models based on fuzzy membership, such as those designed with NetWeaver, are commonly used to express strength of evidence for propositions that the model is entertaining (Figure 8-4). In this context, fuzzy logic is being applied in the sense of interpretation, and the model can be construed as a form of formal argumentation (Halpern 1989). Similar to Bayesian networks, however, a fuzzy membership function also can be used to express subjective probabilities (Zadeh 1968), in which case it may not be immediately obvious which form of knowledge representation is most preferable. As a basic guide:

- Bayesian networks are clearly preferable to fuzzy models if the problem at hand can be strictly represented in terms of the likelihood of events, and actual data are available to estimate the likelihood of those events.
- Bayesian networks may still be preferable to fuzzy models if the problem at hand can be strictly represented in terms of subjective probabilities (replacing the likelihood of events). The case for the Bayesian preference is not nearly as compelling in this situation, but the concepts of linguistic uncertainty underlying fuzzy logic are much less familiar to potential users and their clients, and this could be perceived as a liability, albeit not a major one.

- For more general problems involving both prediction and interpretation, or strictly interpretation or classification, fuzzy models become the better choice.

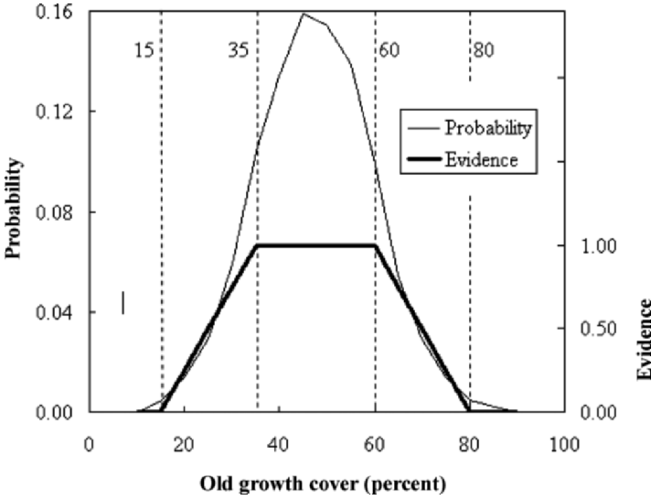

Figure 8-4. Specification of a formal argument with fuzzy logic.

5. MULTICRITERIA METHODS

The early successes of operations research (optimization) methods, described above, resulted primarily from their focus on well-constrained problems in tactical planning. These methods were initially developed to address needs in industrial and business operations, where inputs, outputs, resources, actors, flows, and other problem components could be described with completeness and certainty. Gradually these operations research methods were applied to planning in forest and natural resources management – primarily timber harvesting, transportation, and processing with their similarities to industrial operations.

Traditional optimization-based decision analysis has excelled in addressing mathematically well-defined problems and in addressing the quantitative components of larger problems. Nevertheless, numerous sources (e.g., Klein and Methlie 1990, Gigerenzer and Todd 1999; Levy et al. 2000, Romero and Rehman 2003) have noted that such formulations, while mathematically and logically sound, simply do not reflect real-life problems faithfully enough. In reality, the decision maker is frequently looking for a *compromise* among several objectives. To address this new class of decision problems, multiple criteria decision making (MCDM) techniques were developed beginning in the 1970's. Stewart (1992) provides a review of those approaches. While optimization methods aim to maximize a single criterion over a non-enumerable solution space, MCDM maximizes the aggregate contribution of several criteria (or attributes) over a relatively small set of solution alternatives.

5.1 Multi-attribute utility theory

One of the earliest MCDM methods is multi-attribute utility theory (MAUT) or value theory (Keeney and Raiffa 1976, von Winterfeldt and Edwards 1986). In its simplest form, MAUT provides a set of utility functions (one function for each attribute, or performance indicator), and then scores each decision alternative on each attribute. Scores across all attributes are combined for each alternative (often using an additive model), with individual attribute scores being appropriately scaled for comparability and weighted according to importance. The decision alternative with the highest aggregate utility (or value) score is then preferred. This general MAUT framework has spawned a large number of variants. Each variant modifies one or more aspects of the traditional implementation: to assign weighting values, to scale attribute scores, to combine scores across attributes (e.g., non-additive models), to elicit utility functions, etc. As a result, MAUT has been modified in a wide variety of ways. Furthermore, MAUT has been augmented by other multiple criteria decision methods and other decision aides to make it more complete in some cases, and to improve its applicability in other cases.

5.2 Analytic hierarchy process

Another MCDM approach that was developed about the same time as MAUT and has all its basic characteristics is the analytic hierarchy process (AHP). The AHP, developed by Saaty (1977), provides for: decomposition of the decision problem into a multi-level hierarchy of criteria, direct pair-wise comparisons of the decision alternatives (or alternatively, rating them individually), and rigorous mathematics to generate a preference structure for the alternatives. Schmoldt et al. (2001) describe many applications of the AHP to environmental and natural resources decision making. While many have used the AHP as an MCDM technique by itself, others have used it in combination with other MCDM methods (e.g., Prato 1999, Lexer 2000, Hill et al. 2005). In other MCDM developments, Leskinen et al. (2003) have used statistical methods to estimate ecological values and to account for interactions among the decision variables. Drechsler (2004) demonstrated the integration of quantitative population models with MCDM to evaluate decision conflicts. Recently the network structure of the analytical network process has been used to model the complexity of forest decision problems in evaluating sustainable forest management strategies by using a criterion and indicator approach (Wolfslehner et al. 2005). These several examples, and many others not cited, attest to the versatility and extensibility of MCDM methods in general.

6. INTEGRATED SYSTEMS FOR FOREST MANAGEMENT

By the late 1980s, the scope of forest management began to expand dramatically as agencies, universities, and industry began to embrace new concepts such as the hierarchical organization of ecosystems (Allen and Starr 1982) and forest ecosystem management (Holling 1978, Walters 1986). With an emphasis on broad, holistic, integrated perspectives, the concept of forest ecosystem management posed serious new challenges to the delivery of effective decision support (Schmoldt and Rauscher 1996, Rauscher 1999). The challenge was further exacerbated by the still newer concept of sustainable forest management (SFM) that had risen to prominence, following the Earth Summit in Rio de Janeiro, Brazil in 1992, and by introduction of the adaptive management concept (Walters, 1986, Walters and Holling 1990). While adaptive management as a strategic guide has been useful, much about sustainable forest management remains a moving target. Consequently, holistic and integrative software tools have evolved largely through a trial and error development process.

Most of the DSS technologies discussed up to this point can be described as single-purpose systems designed for problems with a relatively specific focus. In contrast, spurred by the new challenges of ecosystem management, adaptive management, sustainable forestry, and similar concerns, a new class of systems began to emerge in the 1990s. Rauscher (1999) characterizes these new technologies as more “full-service” systems, in the sense that they integrate a few to several features and functions that collectively are designed to accommodate larger, more complex and abstract issues requiring decision support.

Reynolds (2005) provides a critique of three full-service systems that have achieved substantial recognition and are in relatively wide used: the Landscape Management System or LMS (http://lms.cfr.washington.edu), NED (Twery et al. 2003, http://www.fs.fed.us/ne/burlington/ned), and the Ecosystem Management Decision Support (EMDS) system (Chapter 18, Reynolds et al. 2003a). A brief overview of each, from Reynolds (2005), is presented in the following subsections. A fourth system, Woodstock (http://www.remsoft.com), comparable to the others and notable for its success as a commercial application, is also discussed.

6.1 LMS

A wide variety of software applications are available to support decision making in forest management, including databases, growth and yield models, wildlife models, silvicultural expert systems, financial models, geographical information systems (GIS), and visualization tools (Schuster et al. 1993). Typically, each application has its own interface and data format, so managers must learn each interface and manually convert data from one format to another to use combinations of tools. Considering the scope of topics that may need to be addressed in a typical ecosystem management problem, and consequently the need to run several to many applications, manual orchestration of the entire analysis process can quickly become a significant impediment. LMS relieves this problem by managing the flow of information through predefined pathways that are programmed into its core component.

LMS integrates landscape-level spatial information, stand-level inventory data, and distance-independent individual tree-growth models to project changes on forested landscapes over time. The core component of the application coordinates the execution of, and flow of information between, more than 20 programs, including a variety of utilities for data management such as formatting, classification, summarization, and exporting.

Stand projections in LMS are performed with variants of the Forest Vegetation Simulator or FVS (Crookston 1997) or ORGANON (Hester et al. 1987). A variety of utilities report stand projection information in tables and graphs, and projection information can be delivered to the ArcView GIS (Environmental Systems Research Institute) for additional spatial analysis, or to the Stand Visualization System (SVS) or to the Envision landscape visualization system (McGaughey 1997). Both forms of output data can be valuable. In some cases, it is useful to analyze projection data further using a spreadsheet or statistical software, while other times it is most instructive to simulate the appearance of a stand to qualitatively assess spatial landscape features (e.g., scenic vistas).

6.2 NED

NED version 2.0 assists natural resource managers with project-level planning and decision-making processes, and is designed to be used by a forest management professional as a communication tool for working with forest landowners. NED is a goal-driven DSS that implements the Mintzberg et al. (1976) multiple-criteria decision-analysis process. Resources currently addressed include visual quality, ecology, forest health, timber, water, and wildlife. The system is adaptable to a range of applications from small private holdings to cooperative management across multiple ownerships. NED supports a five-step process:

1. Identify and define goals and their measurement criteria.
2. Inventory the property being managed.
3. Design alternatives to manage the land and satisfy the goals.
4. Simulate the impact of each alternative to visualize how the forest will look under each alternative.
5. Evaluate how well each alternative satisfies the hierarchy of goals, and possibly cycling back to step 3 to refine alternatives (e.g., an iterative process).

Extensive hypertext support provides information about resource goals, desired conditions that support the goals, data used to analyze forest condition, and detailed information about the program itself and the rules and formulae used to produce analyses.

NED uses a blackboard architecture and semi-autonomous agents to manage a variety of applications for the user (Nute et al. 2003). In the blackboard approach to problem solving, the current state of the solution is maintained in a global data store (i.e., the blackboard). Agents with specialized knowledge contribute their knowledge, incrementally building up a solution. Finally, a controller agent implements one or more solution strategies to orchestrate when and how other agents contribute to the solution (Nii 1989). The specialized agents participating in a blackboard solution are said to be semi-autonomous, as opposed to autonomous (Maes 1991), because they carry out their tasks under the supervision of a controller. In their simplest form, semi-autonomous agents have state (they "know" certain facts), and behavior (they perform certain tasks when certain states are recognized). Each specialized agent in NED, for example, has the procedural knowledge – or methods in the sense of object-oriented design (Booch 1995) – needed to operate a class of decision support tools needed in forest management. The simulation agent sets up input for growth and yield models and interprets model output. The GIS agent merges information with an ArcView shape file and invokes ArcView to display the information. The visualization agent generates input for SVS and Envision (McGaughey

1997). The NED blackboard is implemented as a data base with integrated Prolog clauses, and is managed by a controller agent. The interface agent provides access to all applications in the system through a single user interface. Additional agents support development of alternative treatment plans; provide analysis of timber, wildlife, water, ecology, and visual goals; and generate a wide variety of reports relevant to forest management. The net effect of tool integration in LMS and NED is similar: transparent flow of information among collaborating system components, resulting in improved ease of use for end users. However, from a development perspective, the agent architecture of NED more readily supports continuing system evolution by better facilitating integration of new decision support tools as they become available.

6.3 EMDS

The Ecosystem Management Decision Support (EMDS) system (version 3.1) is an extension to ArcMap, a component of the ArcGIS 9.0 (Environmental Systems Research Institute, Redlands, CA), that provides integrated decision support for environmental evaluation and planning at multiple spatial scales (Reynolds et al. 2003a). System architecture is based on the Microsoft Component Object Model (COM) specification, which supports the evolutionary design and implementation of complex systems by establishing communication standards that facilitate collaboration among system components (Potter et al. 2000). The practical significance of conformance to the COM specification is the ease with which the functionality of applications can be extended by integration of new components, as is well illustrated by the extensibility of ArcGIS itself via COM-based extensions.

The evaluation component of EMDS, implemented by Rules of Thumb (North East, PA), uses the NetWeaver logic engine (also Rules of Thumb) to evaluate knowledge bases, represented by networks of topics, concerning the state of landscape features. In design of a NetWeaver model, a topic for evaluation is represented by a testable proposition. The statement of a particular proposition may be quite vague. For example, in the SFM context, the statement, "The forest ecosystem is sustainable," clearly is relevant, but also quite vague. However, the formal logic specification underlying a proposition makes the semantic content of the proposition clearer and more precise (see Reynolds et al. 2003b for an extended example). The proposition about forest ecosystem sustainability evaluates as *true to the degree that* its premises are satisfied. The phrase, "true to the degree that," reflects an approach to problem specification that might be termed "evidence-based reasoning," and is implemented in NetWeaver models with fuzzy math (Miller and Saunders 2002), a branch of applied mathematics that implements qualitative reasoning as a method for modeling lexical, as opposed to stochastic, uncertainty (Zadeh 1975a, 1975b, 1976). The reader is referred to the Fuzzy Networks section above.

The planning component, implemented by InfoHarvest (Seattle, WA), evaluates AHP decision models, components of which may optionally implement the Simple Multi-Attribute Rating Technique or SMART (Kamenetzky 1982). The SMART method evaluates attributes of alternatives with utility functions and, in the context of landscape planning, facilitates evaluating an arbitrary number of alternatives.

Logic models and decision models used in EMDS are built by application developers with the NetWeaver Developer (Rules of Thumb) and Criterium DecisionPlus (CDP, InfoHarvest) applications, respectively. The complete suite of applications (EMDS, NetWeaver Developer, and CDP) collectively provides a general application framework. An individual EMDS project may include evaluation and planning at multiple spatial scales, and networks of dependencies between scales can be designed by application developers by summarizing model outputs from one scale and passing them as inputs to models at coarser or finer scales. For example, knowledge base outputs from a biophysical evaluation of watersheds and a socioeconomic evaluation of counties may be summarized for input to the evaluation of biophysical provinces or ecoregions.

6.4 Woodstock

The Remsoft Spatial Planning System (RSPS) is a commercial software suite for long-term forest management planning (Remsoft 2005). The system integrates four separate components that work together to help forest managers formulate strategic management plans that are feasible both tactically and operationally. In contrast to the first three general DSS discussed in this section, all of which at least tend toward more ecological applications, the RSPS suite provides capabilities for very explicit support of commercial business operations in forest management.

Woodstock is the strategic model-building component of RSPS, and provides the core functionality upon which the other components build. Woodstock provides a generic modeling framework within which user-defined models can be specified to address almost any type of land management problem. Modeling solutions are obtained by simulation, optimization, or a combination of the two methods. Typical applications might include any of the following objectives:

- Sustainable management of wood supply, habitat, biodiversity, watershed management, and other forest values.

- Management to meet forest certification criteria.
- Design and evaluation of harvest schedules and treatment regimes.
- Evaluation of economic efficiencies such as present net value.

The Allocation Optimizer component provides resource planners and managers with a tool to develop and assess strategies that allocate wood products to markets by considering wood supply origins, product transportation costs, delivered wood product prices, destination demands, and inventory capacity. Typical applications of this component include:

- Assessing multiple strategies for allocating wood fiber.
- Assessing open-market wood purchase strategies.
- Maximizing total revenue by allocating products to destinations.
- Minimizing haul costs by associating treatment decisions with transportation costs.
- Identifying wood production bottlenecks.
- Identifying future wood supply problems for existing mills.
- Exploring the consequences of adding or closing a mill.

The Spatial Woodstock component supports management and analysis of spatial data. It functions as a map viewer and data manager for viewing, reporting, and analyzing results from the other three system components. A basic objective underlying this component is the ability to represent knowledge about spatial relationships that can help assess the operational feasibility of plans. For example, insights gained from mapping the locations of current and future management activities can be fed back into Woodstock and Stanley (discussed next) to develop more operationally feasible plans.

The final RSPS component, Stanley, is used to build and schedule spatial harvest units, conditioned by specifications in the strategic Woodstock plan. Stanley provides a transition to the operational level by automatically blocking and spatially scheduling all aspects of a management plan. Blocking and scheduling is accomplished by aggregating forest polygons into harvest units subject to minimum and maximum constraints on block size and other spatial constraints and decision criteria established in the Woodstock strategic management plan.

7. RELATIONS BETWEEN DECISION TOOLS AND OTHER TECHNOLOGIES

Up to this point, we have presented software systems for decision making more or less in isolation. However, as the scope of chapter topics in this book should make clear, numerous types of computer-based applications are now being brought to bear to support (usually) specific facets of sustainable forest management. An understanding of how each class of application contributes to supporting sustainable forest management is certainly a valuable starting point for forestry practitioners, and this, indeed, is a major goal of this book. However, as Shao and Reynolds (Chapter 1) discuss, it is at least as important for practitioners to understand how the various classes of applications can be employed collaboratively to achieve the broader objective of implementing sustainable for management.

So, how can computer-aided decision making fit in with, or complement, other types of computer applications? First, and perhaps most obviously, many of the technologies discussed in this book are designed to support landscape characterization (Chapters 2 and 3), and, as such, may provide the raw data and information on which a decision-support application operates. In some cases, a decision-support application may operate directly on this raw information, but in many cases the input required is some form of statistical summary provided by applications such as those discussed in Chapters 5, 6, 7, and 9. In either case, there is a flow of information from some other computer-based applications to the decision-support application.

Unfortunately, it has not often been appreciated that information flow in the reverse direction can be at least as valuable, especially with respect to improving implementation efficiency for processes such as adaptive management (Maser et al. 1994). Too often, groups of natural-resource experts have prescribed data requirements, for landscape assessment for example, on an *a priori* basis, with no formal analysis of how the data to be collected will be evaluated to answer the questions posed by the problem at hand. Such approaches to data requirements can result in either failing to recognize the need for critical information until late in the overall process, or collecting information that is never used. On the other hand, use of computer-aided decision tools early in management processes such as landscape assessment has the potential to achieve significant efficiencies by formally mapping relations between questions to be answered, states and processes that need to be considered, and data (Reynolds 2001a, 2001b). The result is better tailored data collection, which may reduce costs and will help ensure that the information collected is commensurate with the decisions that one expects to make.

8. FUTURE DEVELOPMENTS

Having reviewed an array of contemporary technologies in this chapter that support decision making, it seems appropriate to conclude by speculating a little on the direction of further developments in the near future. Of course, predicting the future is always a rather risky proposition, so we will avoid being overly specific, and instead consider what seem to be three major cross-cutting trends that apply more or less generically.

8.1 Internet-based implementation

The Internet already has opened up interesting possibilities for real-time collaborative application development. With the advent of powerful Internet-meeting services in the past few years, it is now relatively easy for a diverse group of geographically dispersed experts, perhaps representing various disciplines relevant to some issue in sustainable forestry for example, to collaborate on the design of a DSS application. Most contemporary DSS are still run by individuals working on desktop computers, so it is worth noting that the desktop-development environment is not necessarily a serious constraint in this context. Indeed, the authors have worked with a number of groups over the past few years, collaboratively developing desktop applications by means of Internet-meeting services. However, new technological advances continue to open up new, perhaps even more promising, possibilities.

The past few years have seen a steady migration of decision-support technologies to internet-based implementations, in which applications can be run or even developed online (e.g., a simplified forest vegetation simulator called 4S-Tool, http://www.purdue.edu/apps/forestry/4STool). At least a few of the systems described in this chapter, for example, now offer internet-based versions. The trend toward such solutions is likely to continue because this mode of delivery has some clear advantages to software developers in terms of system maintenance and obviating the need for distribution and associated support services.

There are potential benefits to user communities as well. In particular, there is the real potential for improved access to advanced software systems among users in developing countries because they can purchase an analytical service on an as-needed basis rather than purchasing the system outright, which might be prohibitively expensive. Also, Internet applications often have few limitations on which hardware or software (e.g., operating system) the end-user must have available.

An Internet-based implementation is also accessible anywhere and anytime, as long as an Internet connection exists, rather than traditional software installations on a limited number of computers. In addition to, or instead of, online development of applications, some newer systems now provide the ability to export analysis products to the internet for broad dissemination. Given the strong emphasis on so-called e-Government initiatives in the United States and other developed countries, this Internet-based trend is very likely to continue.

8.2 Systems integration versus collaboration

Over the past few decades, computer-based aids to decision making have been increasing in number as well as in their sophistication with respect to the scope and complexity of problems that they can handle. Significant advances often have been achieved through integration of different functions, some examples of which were discussed in section 6. However, systems integration is not always necessarily the best solution, at least initially.

Many of the systems now available could be considered complementary to one another, but each is typically a complex system in its own right, so that the creation of new hybrid systems out of two or more independent ones is usually not trivial, and can be a complex, slow, and expensive proposition. The case for systems integration may seem compelling for specific combinations of systems, but, rather than rush too quickly into a program of integration, a better short-term approach may be to test integration concepts by operating the systems independently, but collaboratively. In effect, this approach amounts to simulating how the integrated system should operate.

In contrast to the foregoing discussion in this section, newer software design concepts such as those based on Component Object Models (COM) and semi-autonomous agents (e.g., NED) have opened up possibilities that have been facilitating systems integration, particularly in the last decade. Recent advances in the implementation of EMDS version 3.0 (section 6), for example, were facilitated by COM. Many current decision systems could be described as legacy systems insofar as their design predates standards such as COM. However, as platform-independent technologies such as .Net, Simple Object Access Protocol (SOAP), and Extensible Markup Language (XML) are increasingly adopted for new systems development, or for redesign of existing systems, opportunities for relatively easy systems integration as well as migration to Internet implementations (section 8.1) are likely to continue increasing as well.

8.3 Accommodating the human dimension

The evolution of computer aids to decision making has been largely driven by advances in technology (Ekbia and Reynolds, in press), and most systems have been developed to support a rational model of decision making in the sense of Mintzberg et al. (1976). However, in recent years, social scientists, working in the field of decision theory, have been advancing new approaches, based on concepts such as collaborative or mutual learning (Daniels and Walker 1996), dialectic approaches (Elgarah et al. 2002), social DSS (Turoff et al. 2002), and similar ideas. Most of the new approaches focus on decision support in a group or public context, which is certainly appropriate, considering that the problems being addressed today are often large and complex, requiring the collaboration of many specialists, and are often played out in very public settings.

Because single individuals rarely make natural resource management decisions, group decision making has become a priority topic—at least in the MCDM community—but applying equally well to the broader DSS arena. Empirically, we have come to understand that group decisions are typically better than average individual performance, but rarely as good as the best individual. Hence, while there are many other reasons to engage groups in decision processes, consistently making the best decision choices is not one of them. Reasons for participatory decision making include: broad ownership in the decisions and their implications, support for implementation of decisions, more complete coverage of all pertinent issues and viewpoints during the decision process, and the appearance of an open and inclusive decision process. There are numerous examples of research and case studies on group-based DSS for forestry and natural resource management (*q.v.*, Schmoldt et al. 2001, Rauscher *et al.* in press). Given the growing importance of inclusive and open decision processes in forestry, it is reasonable to assume that participatory decision making will continue to generate new developments in DSS. The movement toward Internet-based DSS implementations opens up greater possibilities to engage decision makers at dispersed locations through virtual meeting environments; these currently include such things as group whiteboards, document and application sharing, audio/video connectivity, voting, and Delphi processes. For DSS that operate at multiple scales, decisions made at a regional level could then be handed down and incorporated into multiple, subregional decision-making processes. But, instead of regional decisions being policy mandates as is currently done, regional decisions would transparently filter down to tactical and operational decision making at the finer scales, through the DSS. This has broad implications for organizational decision making and how tightly an organization couples that activity with DSS tools.

There has been a strong tendency to present the new approaches as alternatives to the rational approach on the grounds that the latter is unworkable in the context of managing ecosystems and sustainable forest management. It may be more constructive, however, to explore the proposition that rationality is a necessary, but not sufficient, condition for decision making in the new context of forest management. Consider that a basic definition of rational is simply, “able to be reasoned about.” We find it difficult to imagine how the new approaches can succeed if there is not a rational core to the decision process by which the multiple alternative views can be rendered mutually understandable, providing a foundation for constructive dialogue. Ekbia and Reynolds (in press) explore these ideas further, and demonstrate how rational models and the newer concepts from decision science can complement each other in decision-making processes.

Much more research into this area will be required to make significant progress, but this line of inquiry also may prove to be one of the most profitable for advancing the application of computer-aided decision making in the next several years.

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Chapter 9

BIOECONOMIC AND MARKET MODELS[*]

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Abstract: The United States has a century of experience with the development of models that describe markets for forest products and trends in resource conditions. In the last four decades, increasing rigor in policy debates has stimulated the development of models to support policy analysis. Increasingly, research has evolved (often relying on computer-based models) to increase understanding of consumer demands, producer behavior, landowner behavior, and conditions of the timber resource. Greater computational power available since the mid 1970s has allowed the evolution of bioeconomic models that combine economic and resource models. These are used in the United States to provide the basis for forecasting future resource and market trends and to inform policy analysis. These more complex models have also extended options for policy analysis using approaches such as scenario planning to help decision makers gauge uncertainty.

Key words: Forest sector modeling; policy analysis; supply; demand.

1. INTRODUCTION

For the past century, forest policies of the United States have been influenced by information about economic efficiency and equity developed increasingly from models of various economic and biological processes. In the past four decades, these models have grown in size and complexity, enabled by rapid developments in computational power. The purpose of this Chapter is to describe the development of both market and bioeconomic models, and to

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describe their use in policy analysis. Needless to say, the impact of this information on strategies for land management and forest policies has been evocative.

This chapter will proceed in several steps. First, given that models need to reflect local conditions, the U.S. forest context is briefly summarized. Second, the evolution and structure of market models are summarized. Third, three uses of these models are discussed: forecasting, policy analysis, and scenario planning (strategic assessments). Finally, lessons learned are discussed, including inferences about the importance of frameworks for an integrative assessment as a basis for policy analysis.

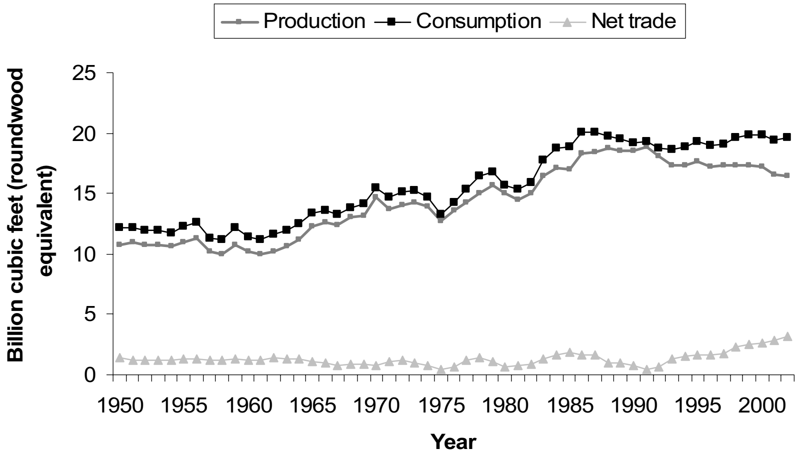

Figure 9-1. Production, consumption, and net trade of timber products, 1950-2002.

The forest situation in the U.S. provides a rich setting for analysis of the forest sector. Powell et al. (1993) and Smith et al. (2001) provide a detailed description of the U.S. timber resource. Briefly, the U.S. forestland base is 298.3 million ha that includes 197.9 million ha of timberland defined by productivity and availability for harvest. The U.S. forestland per capita is roughly a third higher than the world average. The United States accounts for 7.4% of world resources but 27% of consumption and production of industrial wood. Growth in consumption and slower growth in production (and as a proxy for harvest) is shown in Figure 9-1. The United States is a net importer of forest products and its largest trading partner is Canada. These trends reflect a multitude of underlying trends including growth in population, disposable income, and consumer preferences for forest products.

Unlike most other countries, the largest share of timberland (73%) in the United States is privately owned: 28.5 million ha by forest industries, and 116.3 million ha by a variety of owners including farmers and others who do not operate wood-using plants. Publicly owned timberland accounts for the reminder, with the federal government being the largest public owner. Federal lands comprise about 20% of all U.S. timberland and 34% of all forestland. The federal government plays a dual role. First, it regulates markets and environmental conditions and, second, it is a major land manager. These dual roles have led to a range of U.S. forest policies that address issues such as terms of trade, performance and quality standards, safety regulations, pollution abatement, as well as policies for the management of federal lands.

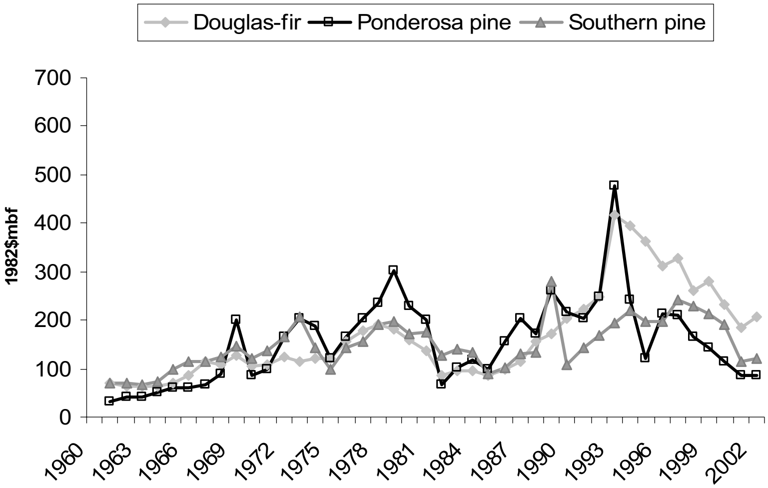

Figure 9-2. Stumpage prices for Douglas-fir and ponderosa pine softwood sawtimber, 1910-2004.

Private timberlands have fostered the development of functional markets for forest products. Figure 9-2 illustrates the dynamic nature of markets for stumpage (a factor of production) in the Pacific Northwest and South. It also shows the persistent differences in regional stumpage prices. Both the highly dynamic nature and regional differences among markets challenge the development of empirically based models.

Finally, the United States has a rich tradition of science-based policy development. Research information plays three roles in this context: (1) providing specific information needs of managers and policy makers; (2) development of systematic approaches to complex problems; (3) and provision of more rigorous understanding of processes for which management has often relied on intuitive approaches.

2. QUESTIONS LEADING TO MODEL DEVELOPMENT

There are several types of questions that compelled the development of computer-based bioeconomic models. The first type focuses on understanding market forces and understanding market performance. The second type deals with models used to understand the impacts of policies. The third type deals with attempting to estimate relative uncertainties associated with various policies.

The theoretical and methodological roots of these models owe much to developments in the economics and agricultural sectors. In the economics sector, Samuelson (1952) conceptualized the equilibrium conditions in spatially distinct markets leading to efforts to use programmatic approaches to solve for the prices, quantities, and trade flows that maximize the sum of consumer and producer surplus. In the agricultural sector, the development of macro-econometric models in the late 1960s and their use in policy simulation experiments (see for example Naylor 1972, who described the form of the policy simulation approach still used today) served as examples for forestry research. McKillop (1967) is often credited with the first comprehensive econometric analysis of forest-product demand using a theoretically complete specification.

The ability to develop policy-relevant market models expanded rapidly in the 1970s, enabled by access to modern computers, more rigorous empirical training of researchers, and the evolution of time-series data for a number of key variables. Policy analysis, that in the past had been based on hypothetical relations, was now based on empirically developed frameworks that proved to be robust in an array of applications.

One outcome of this expanded research capacity was the development of models that represented the complete forest sector.[11] The development of a forest-sector model for the United States was supported by the USDA Forest Service who needed a comprehensive planning framework to meet the requirements of the Resources Planning Act (RPA).[12] This forest-sector

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[11] See Haynes, 1993 for a synthesis of the development and uses of forest sector analysis.

[12] The Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974 as amended by the National Forest Management Act of 1976 directs the Secretary of Agriculture to prepare a Renewable Resource Assessment. The purpose of this Assessment is to analyze the timber resource situation in order to provide indications of the future cost and availability of timber products to meet the Nations' demands.

model (the Timber Assessment Market Model [TAMM] (Adams and Haynes 1980, Haynes and Adams 1985, Adams and Haynes 1996) provided an integrated structure for considering the behavior of regional prices, consumption, and production in both stumpage and product markets. TAMM has been used for the past two decades to provide forecasts of market activity and to explore the need for, and the consequences of, various policy actions.

3. THE U.S. TIMBER ASSESSMENT MODEL

Figure 9-3 shows the bioeconomic modeling framework used to develop projections for timber assessment. This structure has evolved over the past 25 years to fill needs for greater geographic, owner, resource, and product specificity in the projections. The framework consists of four submodels or modules:

TAMM embraces the solid wood-products sector and also provides the linkage between product markets (solid wood and pulpwood) and timber inventory.

The Aggregate TimberLand Analysis System (ATLAS) is a biological modeling structure for projecting timber growth and inventory over time given timber harvest.

The North American Pulp And Paper model (NAPAP) is an economic model of the pulp, paper, and paperboard sector with detailed treatment of fiber supply (recycled, roundwood, and short-rotation woody crops) used to project markets for pulpwood stumpage.

The AREACHANGE model explains the shifting of timberland between forest and nonforest uses and among forest types.

The system shown in Figure 9-3 is an example of a bioeconomic model, because it combines explanations of both biological and economic processes. Figure 9-3 also shows the major links between modules. Harvest estimates lead to adjustments in timber inventories (and broad-scale vegetation conditions) given changes in forest growth and losses and gains in timberland. The volume of available timber inventory is then fed back to both the solid wood and paper and paperboard models as a major determinant of stumpage supply. The economic models are built on spatial

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The analysis also identifies developing resource situations that may be judged desirable to change and it identifies developing opportunities that may stimulate both private and public investments.

equilibrium concepts that solve for simultaneous equilibrium in both regional product and stumpage markets.

These models were developed to support national assessments of supply and demand trends for timber. Starting in the 1950s, the USDA Forest Service developed an assessment framework, based on a trend analysis of future demands for forest products and the availability of timber resources as separate entities (USDA Forest Service 1958, 1965, 1974, 1982). Policies and emerging trends were discussed in the context of the gap between the trajectories of the demand for forest products (expressed in roundwood equivalents), and the prospective availability of timber. Prices were not explicit in this analysis. Computer models were used in projecting demand and inventory, the latter by means of a stand-table-based inventory projection called TRAS (Larson and Goforth 1974, Alig et al. 1982).

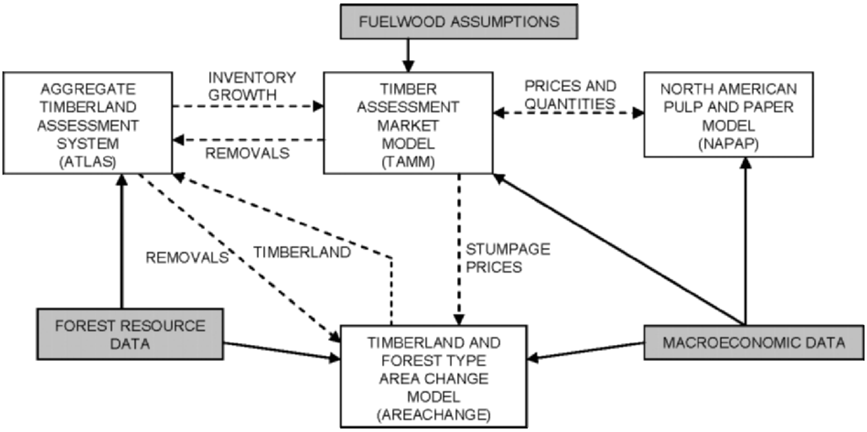

Figure 9-3. Bioeconomic modeling system for the Timber Assessment.

The development of more elaborate computer-based models was strongly influenced by changes in the ways in which timber policy issues were characterized, shifting from potential shortfalls in future quantity toward a focus on future price trends and impacts. Starting in 1977, the USDA Forest Service undertook the development of a forest-sector model designed to explicitly describe regional stumpage price behavior as required by RPA. The resulting model was called TAMM (Adams and Haynes 1980, Haynes and Adams 1985, Adams and Haynes 1996). It produced regional price trends in both product and factor (stumpage) markets that recognized simultaneous market interactions and differences in regional timber resources.

Subsequent refinements of these models continue to provide useful policy-relevant information. The modeling approaches are especially apt in light of ongoing debates about resource sustainability, because many of these discussions revolve around notions of balancing timber demands and supplies with changes in resource conditions.

3.1 The timber assessment market model

Since its initial development in the late 1970s, TAMM has undergone a number of extensions and revisions designed to improve the behavioral models underlying its projections and the utility of its output to resource analysts and policymakers. Details about the various input assumptions used in TAMM are described in the 1989 assessment (Haynes 1990), the 1993 assessment (Haynes et al. 1995), and model features in Adams and Haynes (1996).

TAMM is a spatial model of the solid wood and timber inventory elements of the U.S. forest products sector, and of softwood-lumber and oriented-strand-board (OSB) production in Canada (Adams and Haynes 1980, 1996; Haynes and Adams 1985). TAMM provides annual projections of volumes and prices in the solid wood-products and sawtimber-stumpage markets and estimates of total timber harvest and inventory by geographic region for periods of up to 50 years. Projections of pulp and paper products are derived from the NAPAP model (Ince 1994), which is linked to TAMM through the quantities and prices of roundwood and residues. Endogenous trade flows in TAMM are limited to softwood lumber and OSB/waferboard shipments between the United States and Canada. All other flows, including sawlog imports and exports, are established externally.

The major modules in TAMM are outlined in the following sections.

3.1.1 Product demands

There is one set of product demand relations for each of the major products modeled in TAMM: softwood lumber, softwood plywood, OSB/waferboard and hardwood lumber. These relations explicitly recognize the opportunities for substitution among these classes of products, and so are interdependent in product prices (contemporaneous price-based substitution).

The demand module for softwood solid wood products uses Spelter's diffusion analysis of demands for U.S. softwood lumber, softwood plywood, and OSB/waferboard (Spelter 1984, 1985, 1992). Spelter's model considers the demand for each product category in various end uses (several components of single-family home construction, residential upkeep and alteration, multifamily and mobile units, nonresidential construction, manufacturing, and shipping, a total of 18 uses in all). Demand for hardwood lumber is disaggregated into eight end-use categories (furniture, millwork, flooring, ties, pallets, mining, containers and dunnage, and miscellaneous). Demand relations employ an “end-use factor” form and, as in the case of softwoods, are dependent on prices of substitute materials in the current period. In general, aggregate product demands have been found to be inelastic with respect to changes in price in the short term. Sustained price increases, however, lead to consumers making adjustments in consumption patterns, and act to increase effective demand elasticities two to threefold or more (depending on the end use) over a 5-year period.

3.1.2 Product supplies

In RPA timber assessment projections, it has been customary to treat trends in the technology of wood-products processing and logging by means of specific scenarios of future technical developments and associated impacts on use of the wood (log) input. Efficiency of wood use in milling is represented by “product recovery factors:” product output-log input ratios (for example, board foot lumber tally output per cubic foot log input). To explicitly incorporate these projections in the representations of product supply, the module for solid wood-products supply assumes that product output is obtained in fixed proportions to log input (the product recovery factor linkage), but in variable proportions to all other factors. This implies that logs are separable from other inputs in production. Details of the derivation of relations in this module are described in Adams and Haynes (1996). These are econometric relations with parameters estimated using historical time-series data. Canadian supplies of softwood lumber and OSB/waferboard are explicitly represented in this module and are integral, price-sensitive elements. Estimated product supply elasticities with respect to product price differ markedly across regions and products. Although most are inelastic, many, including those for the largest producing regions, are close to unit elasticity.

3.1.3 Log demands

Given the assumptions of fixed log input-product output relations in TAMM, the derived demand for logs is simply the product of recovery factors times output. This same accounting allows the model to track residues generated in the production process and their disposition. Estimated residues generated in milling depend on projections of product recovery, size of logs processed, and the size mix of products.

3.1.4 Log and timber supplies

The supply of wood to processing facilities is modeled as a mixture of price-sensitive relations and exogenous flows describing the volumes of timber available for immediate harvest and the volumes of logs delivered to mills. Harvests from public lands are set outside the projection model as a policy input. Private relations for timber supply derive from explicit theories of multi-period harvest behavior for industrial and nonindustrial owners (Adams and Haynes 1996). The resulting relations link harvest to prices, inventory, interest rates, and, for nonindustrial private forest owners, income from nonforest sources. Price sensitivity for both softwood and hardwood supplies has been found to be low (inelastic) for all regions and owner groups.

3.1.5 Timber harvest and inventories

TAMM also includes a program module that provides linkage to the ATLAS timber-inventory system described below (Mills and Kincaid 1992) for the solid wood, paper and board, and fuelwood models. Product volumes are aggregated, converted to amounts derived from live growing stock, and adjusted for additional removals owing to logging residues and cultural treatments. This module also allows estimation of timber harvest in Canada, although it does not attempt to model Canadian timber inventories. Canadian harvest estimates are derived from projected softwood lumber, paper and board, and OSB/waferboard production, with adjustments for softwood plywood, hardwood lumber, nonstructural panels, miscellaneous products, and log trade, which are not explicitly modeled.

3.2 The aggregate timberland assessment systems timber inventory

The biological projection system, ATLAS, was developed to model timber inventories at multiple geographic scales[13]. Its function is to simulate growth, harvest, changes in land use and forest type, and shifts in timber management for approximately 144.1 million ha of private timberland and 55.5 million ha of public timberland in the conterminous United States. Inventory projections depend on the development of inputs under several assumptions regarding the stratification and aggregation of the basic timber-resource data. These data were derived from approximately 180,000

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[13] The ATLAS system evolved from earlier work by Beuter et al. (1976) and Tedder et al. (1987).

permanent ground plots maintained by the Forest Inventory and Analysis (FIA) programs within the USDA Forest Service.

At its most basic level, ATLAS uses an even-age representation of the timber inventory. That is, the area and standing volume of the inventory are aggregated into a series of age classes that advance over time to simulate the development of forests. Original field inventory data relate to the stand level, whereas the linkage between TAMM and ATLAS recognizes a highly aggregated regional (multistate) level. Aggregating inventory from the stand level to the regional level combines a broad mix of conditions, and the even-age characterization used by ATLAS gives way, in effect, to a multi-age model in which age classes represent a collection of stands on a similar growth trajectory.

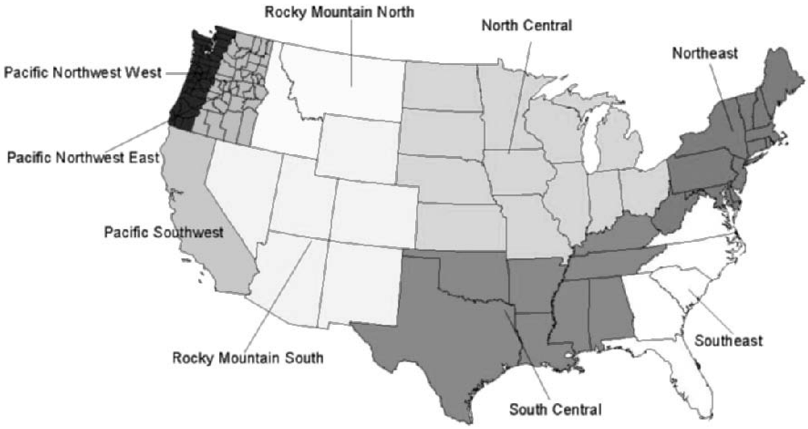

Figure 9-4. RPA assessment regions for the United States.

For the timber assessment, the resource data were divided into nine timber-supply regions (see Figure 9-4). Within each region, timberland was stratified by up to five ownership groups, up to 10 forest types, and up to 26 age classes. Five-year age classes were used in the South and 10-year age classes were used in all other regions. Resource data in the South and the Pacific Northwest West were further stratified by three classes for site productivity and by up to 12 classes for management intensity. Timber-resource data for national forests and other public forests were stratified into three management classes.

The set of attributes used to identify a unit or cell of the ATLAS inventory is region, owner, forest type, site-productivity class, management-intensity class, and age. The area and timber volume within each cell can be identified by these attributes throughout the projection. Weighting within and among cells is dependent on the area associated with each stratum. Given that the stratification scheme depends upon regional aggregations that are sometimes rather broad categories, cells can range in size from several thousand to several million hectares (or acres). The projection mechanism in ATLAS moves each cell along a yield trajectory, dependent on coefficients that adjust volume relative to the user-defined yield of the stratum. This process projects cell volumes forward by age class using a time-step consistent with the length of the projection period. Yield tables for each stratum were derived from either established growth models, or were empirically derived from timberland inventory plot data collected by the various USDA Forest Service FIA units (see Mills, 1990). The various management regimes were derived through cooperative research and consultation with private forest landowners, and from previous studies. The inventory data inputs are summarized in Mills (1989, 1993) and Haynes (2003).

Over time, as an inventory cell advances in age, it can change management-intensity class, shift forest type, receive a harvest treatment, or be lost from the forestland base to nonforest uses such as developed uses (Alig et al. 2003). Upon final harvest, the cutover area within the cell returns to a regeneration pool in which the area is combined with all other land available for regeneration and assignment to a new cell. Depending on the type of harvest, this could be a single cell, several cells, or portions of several cells. The harvested area is combined following final harvest and the area to be regenerated is distributed among the available management classes based on both endogenous and exogenous parameters assigned. A new cell is created at that time. This re-pooling of regenerated area and loss of the original identity is known as a "model II" formulation, as described by Johnson and Scheurman (1977). Cells cease to exist when their inventory is completely harvested, or they are removed due to area loss, or when inventory grows into the oldest age class, and they are added to a larger pool.

In the 2005 Assessment Update, the stratified timberland data occupied over 9,000 cells at the start of the projection. To avoid introducing ambiguous errors to the initial FIA plot data, inventory values were not adjusted to a common starting point in time. The starting year represents roughly the average year the data were collected: 1995 in the South, and 1990 in the seven remaining U.S. regions. To reach 2050, the South was projected for eleven 5-year periods, and all other regions are projected for six 10-year periods. By the end of the projection, some concentration of age and management groups had occurred and the inventory resource was distributed among 7,100 cells.

In each simulation period, changes in the inventory result from growth, area change, and harvesting. Periodic change in inventory volume is the sum of four components: net growth (+), volume lost owing to area loss (–), harvest (–), and volume gained owing to area gain (+). Net growth is the sum of growth (net of mortality) calculated for all inventory present during any portion of the projection period. Normal inventory growth is calculated when cells advance in age, simply moving from one time step to the next, and are present for whole period. A partial period of growth is calculated on the timber volume removed by harvesting and on the volume inventory gained or lost because of additions or subtractions of timberland area.

Changes in forest type and management intensity are governed in part by externally developed scenarios of prospective future private management decisions. Enrollment of area into various regimes of management intensity is also endogenously sensitive to price and other market elements. The market response has been recently incorporated by using costs and returns to generate a series of economic returns to guide the model's investment decisions. In the past, adjustments in management intensity were made using judgments and a series of successive projections to gauge possible price impacts.

While growth is simulated for each cell independent of all other cells, the amount of harvest or area change occurring in a particular cell most often depends on the cell's weight relative to other cells. That is, the amount of harvest allocated and removed, or the amount of area lost, will depend on a cell's relative available volume or relative area among a targeted group of cells. For changes in forest area, this typically occurs within a forest type and for harvest this occurs among the forest types that are grouped together for harvesting. The harvest volumes in the RPA were derived from product demand for hardwood or softwood. Demand was balanced against the available ATLAS inventory in the TAMM portion of the model. Between TAMM, NAPAP, and ATLAS, the inventory and harvest were aggregated to the same region, owner, and fiber type. ATLAS apportions the harvest across all forest types within the harvest group based on available volume among the types and available volume among the cells within each type.

3.3 North American pulp and paper model

The NAPAP model applies conventional techniques for modeling regional markets to compute annual market equilibria, based on optimization of consumer and producer surplus in the pulp and paper sector (Zhang et al. 1993 and 1996, Ince 1999). The model computes market equilibria over a 65-year period, extending historically from 1986 through the present and out to the year 2050. The overlap of model projections with 15 years of actual historical data allows for extensive testing and calibration of model performance (average errors between historical data and projected equilibrium product demands, pulpwood supply, and recycling rates over the historical period are less than 1 percent per year). Changes in regional production capacities for pulp and paper manufacturing processes, including shifts between virgin fiber and recycling technologies, are simulated in the model as economic responses to projected market conditions, and in turn, projected market equilibria are influenced by shifts in capacity and embodied changes in technology. The introduction in the 1990s of somewhat more sophisticated economic modeling techniques, based on market analysis and technology forecasting, resulted in projections of pulpwood market trends lower than those in previous timber assessments, largely because the NAPAP model accurately simulated the impact of increased paper recycling (Ince 1994, 1999).

Whereas TAMM produces projections for solid wood industries and sawtimber markets, the NAPAP model produces projections for the pulp and paper industry, pulpwood markets, and recovered paper markets. The NAPAP model uses linear programming to solve for annual market and production equilibria. Equilibria are adjusted over time by endogenous changes in production capacity and exogenous changes in supply and demand. The NAPAP model shows how markets for pulpwood and recovered paper are expected to evolve in response to changing market conditions, including changing technology (shifts in production capacity embody shifts in technology). The model includes regional supply functions for pulpwood and recovered paper, and a detailed representation of regional production capacity and production volume for all principal grades of paper, paperboard, and market pulp produced in the United States and Canada. The model also includes demand functions for all end products, with separate demand functions for U.S. domestic demand, Canadian domestic demand, and demand for exports outside of the United States and Canada.

The current NAPAP model is an extended and revised version of the original NAPAP model used in the 1993 assessment (Ince 1994, Haynes et al. 1995). Details of NAPAP model methods and results can be found in Ince (1994, 1999) and Zhang et al. (1996). NAPAP model methods are an application of the price endogenous linear programming system (PELPS), an economic modeling system developed primarily for modeling the pulp and paper sector over the past decade (Gilless and Buongiorno 1985, Calmels et al. 1990, Zhang et al. 1993). Commodities in production and demand in NAPAP model are listed in Table 9-1.

In the NAPAP model, there are three demand regions (United States, Canada, and Other World). Separate United States and Canadian demand functions are included for each principal paper and paperboard grade. U.S. demands for paper and paperboard grades are defined by estimated elasticities with respect to product price, per capita U.S. GDP, U.S. population, and price of capital. Equilibrium prices are derived endogenously within the model, whereas other independent variables are projected exogenously. U.S. demands for communication paper grades include also elasticities with respect to price indexes of television or radio and computers. Econometric analysis has shown that demands for communication paper grades and electronic media are complementary, so declining real prices for media such as computers exert a positive influence on demand for paper (Zhang 1995). U.S. demands for packaging paper and paperboard grades include also elasticities with respect to a price index of plastic substitutes and the all-commodity Producer Price Index (PPI). Econometric analysis has shown that plastics are weak substitutes for paperboard grades, and prices of plastic substitutes are not expected to decline significantly (Zhang 1995). Canadian demands for paper and paperboard grades include only elasticities with respect to price and Canadian GDP.

Table 9-1. Commodities in production and demand in NAPAP model

Paper grades	Paper grade market pulps	Paperboard grades and other
Newsprint	Softwood kraft	Linerboard (unbleached kraft and recycled)
Uncoated free sheet paper	Hardwood kraft	
Coated free sheet paper	Recycled	Corrugating medium (semichemical and recycled)
Uncoated groundwood paper	Chemithermalmechanical Pulp (CTMP)	
Coated groundwood paper		Solid bleached paperboard
Tissue and sanitary paper products		Building paper
Specialty packaging and industrial paper		Recycled board (other than corrugated boards)
Unbleached kraft packing paper		Dissolving pulp

Projected growth rates in U.S. demands for most paper and paperboard commodities were also adjusted downward in the period from 2000 to 2005, to more accurately reflect the impact of the current economic recession on the pulp and paper sector. Although domestic GDP growth did not slip into a recession until the third quarter of 2001, U.S. paper and paperboard consumption has been receding from a recent peak of over 341 kg per capita in 1999 to around 318 kg per capita in 2001, and domestic paper and paperboard production has dropped by about 7% in that period. This is the most significant drop in consumption and production since the period of the energy crisis in the early 1970s. Thus, projections of U.S. demand in the NAPAP model incorporate a period of slow growth in the near term, with partial recovery to modest expected rates of growth in demand after 2005.

There are eight pulpwood-supply regions in the model (U.S. North Central, Northeast, South Central, Southeast, West, Canada East, Canada West, Other World), six production regions (U.S. North, South Central, Southeast, West, Canada East, Canada West), and five regions for recovered paper supply (U.S. North, South, West, Canada East, Canada West).

Pulpwood supplies for Eastern U.S. supply regions include supplies from harvests on forest industry lands, harvests on non-industrial private forest lands, harvests on public forest lands, and wood residues supply (from sawmills and plywood mills), for both hardwoods and softwoods (eight distinct sources of pulpwood supply in each Eastern U.S. region). Pulpwood supplies for U.S. West and both Canadian supply regions include supplies from timber harvests and wood residues, for both hardwoods and softwoods (four distinct sources of pulpwood supply).

Functions for supply of pulpwood stumpage were estimated for pulpwood harvest from forest industry and non-industrial private forest lands in Eastern U.S. regions (separately for hardwoods and softwoods). Stumpage supply functions have unitary elasticity with respect to timber inventories, projected by TAMM and ATLAS. Pulpwood supplies were estimated to have relatively low elasticity with respect to stumpage price of pulpwood (less than 0.5 in most cases). Harvest quantities for pulpwood from public forest and total harvest of roundwood pulpwood in the U.S. West are projected exogenously. Supplies of pulpwood residue are determined by lumber- and plywood-production activities projected in the TAMM model. Equations for supply of Canadian roundwood pulpwood are elastic with respect to delivered pulpwood price, sawtimber price, and labor wage rates in Canada (projected exogenously). Supplies of Canadian pulpwood residue are elastic with respect to delivered pulpwood price and Canadian lumber-production activities; the latter are projected in TAMM.

In the NAPAP model, supply of recovered paper is modeled for five categories of recovered paper including old newspapers, old corrugated containers, mixed paper, pulp substitutes, and high-grade de-inked paper. For U.S. supply regions, supply of recovered paper consists of two elements, long-term contract and spot market supply. Large quantities of recovered paper are collected and transferred to mills under long-term negotiated contracts (particularly in the domestic sector). The remainder of the market is an open or spot market (particularly for exports). For purposes of estimating supply of recovered paper, volume of domestic supply was used as a proxy for supply under long-term contract, and volume of export supply was used as a proxy for spot market supply. Supply under long-term contract is modeled as unresponsive to price, but increasing gradually over time in relation to consumption of paper and paperboard commodities (recovery is increasing but at a declining rate over time). Spot-market supply is elastic with respect to price, landfill tipping fees, and consumption of paper and paperboard commodities. Total supplies of the various categories of recovered paper are each limited by assumed maximum feasible recovery rates.

Trade flows are modeled separately for all pulp, paper, paperboard, and fiber input commodities in which there have been significant trade volumes in the past decade. The market equilibria for U.S. pulp, paper, and paperboard imports from Canada are modeled endogenously by the NAPAP model, as influenced by regional production costs and assumptions about rate of currency exchange. Other significant trade flows (total exports from Canada to Other World, total U.S. exports, and total imports from Other World to the United States and Canada) are projected by using trend analysis with significant adjustments for the assumed impacts of expansion of global capacity and rates of currency exchange. In particular, the current outlook for U.S. export of paper and paperboard is more pessimistic than in past assessments because of the observed negative impacts of the strong dollar on U.S. competitiveness in recent years, weakened growth in domestic capacity, and continued expansion of overseas capacity.

3.4 Timberland area change model

The land-area projection system, AREACHANGE, was developed to project changes in land use and forest type at regional and national scales. The system was linked to the ATLAS and TAMM models in the 1989 assessment (Haynes 1990), and the study of “The South’s Fourth Forest” (USDA FS 1988). A projection by the system operates in two phases. In the first phase, area changes in major land uses are projected to provide regional estimates of total timberland area by ownership, e.g., non-industrial private forest. In the second phase, the system projects area changes for major forest types (e.g., planted pine) on each ownership. Price projections from other parts of the timber-assessment modeling system are used as one of the inputs in the first phase of the projections, and projections of changes in class of management intensity from the ATLAS model are used as an input in the second phase (Figure 9-3) (Alig and Butler 2004).

For the first phase, econometric analyses of the determinants of land use by region (e.g., Mauldin et al. 1999, Plantinga et al. 1999, Ahn et al. 2002) were used in developing simulation models to project changes in regional area in timberland by private ownership (Alig et al. 2003). Land-use competition between forestry and other sectors is modeled by using statistical relations between changes in timberland area and determinants such as population, per capita income, and income from land-based enterprises such as forestry or agriculture.

In the second phase, area changes for forest types on a particular ownership can result from four basic sets of activities: afforestation, deforestation, shifts among forest types on retained timberland, and ownership exchanges. In contrast to ecological processes, land-use changes and disturbances can differ significantly by type of private ownership. Changes in land use involving afforestation and deforestation affect areas of forest type over time. Deforestation is most often caused by conversion to other land uses. This contrasts to timber harvests as part of typical forestry activities, because timber harvests are most often followed by regeneration back to forest. Land exchanges between ownerships are largely driven by financial, strategic, and other socioeconomic factors (Alig 1985).

Transitions in forest type on timberland are based on data from remeasured FIA survey plots. Projections of such area changes for major forest types take into account likelihood of final harvest and forest successional forces (Alig and Wyant 1985). Forest-type transitions for an aggregate grouping of timberland (by a stratum representing a specific region and ownership) are conditional on three types of timber harvest–no harvest, final or clearcut harvest, and other harvest types and miscellaneous natural disturbances. Projected harvest information is provided by the overall TAMM/ATLAS/NAPAP/AREACHANGE modeling system.

3.5 Linkage among modeling of area changes, timber management intensity, and economic timber supplies

Solution of the integrated modeling system shown in Figure 9-3 involves an iterative approach. Starting estimates of land use and forest cover from the AREACHANGE system are fed into the ATLAS model, which also accounts for changes in intensity of timber management. Resulting impacts on forest growth are reflected in ATLAS, which adjusts timber inventories. The adjusted physical measures of available timber inventories are used to shift curves for supply of timber stumpage in the economic models of timber supply embodied in the TAMM and NAPAP models. Price projections from the latter models are then fed back to the AREACHANGE system to account for the impacts of any altered timber-harvest levels and timber prices on projections of land use and forest cover. The revised land-use and forest-cover projections are then input into new ATLAS runs, and so on. This iterative running of models proceeds until there is a reasonable convergence of linked model outcomes.

4. USING TAMM, ATLAS, NAPAP, AND AREACHANGE

These forest-sector models are used to provide conditional forecasts, examine the impacts of various hypothetical and actual forest policies, and explore scenarios to develop a sense of the uncertainties of various outcomes.

4.1 Forecasting

One of the motivating reasons for developing forest-sector models is to assist in forecasting (see Kallio et al. 1987 for more details). This role takes advantage of the structural models that comprise forest-sector models and the way in which they capture the interplay among various components including how spatial or dynamic processes function. In the forecasting role, these models provide a quantitative set of estimates about future events, based on relations that embodied past and current events, and estimates of future values for exogenous variables. Such forecasts are said to be conditional in the sense that they are the consequences of both the model and various assumptions about exogenous variables.

The integrated system, comprising TAMM, ATLAS, and NAPAP, was developed to provide forecasts of the prices and trends in timber markets and resource conditions. For example, the RPA 2005 Update base projection envisions continued strong growth in total U.S. requirements for forest products (domestic consumption plus exports) to 2050. Imports will supply a smaller portion of the growth in total wood requirements, and domestic sources a correspondingly larger share, over the next 45 years than was the case during the previous 5 decades. Future harvests from domestic forests alone are expected to grow each year by 0.11 billion cubic feet (bcf), close to the trend over the past 50 years of 0.12 bcf/year (Figure 9-5). At the same time, real growth in product prices will fall below long-term historical rates for nearly all products.

Over the 50 years from 1952 to 2002, U.S. consumption plus exports of all forest products rose by some 9.5 billion cubic feet. U.S. harvest increased by 6.0 billion cubic feet, and imports rose by 3.5 billion cubic feet over this same period (Figure 9-1). Real prices of softwood lumber, hardwood lumber and paper rose (compound rates of 0.8%, 0.4% and 0.3%, respectively), while prices of softwood plywood, OSB (since 1976), and paperboard fell. In the Update base projection, U.S. consumption plus exports increases over the 2002-2050 period by 8.6 billion cubic feet. Imports grow by 1.4 billion cubic feet, while harvest from both forests and short rotation woody crops (SRWC) plantations rises by 7.1 billion cubic feet.[14] Prices of softwood lumber, hardwood lumber and OSB rise slowly (0.2%, 0.3% and 0.1%, respectively), prices of softwood plywood, paper and, paperboard remain stable or fall.

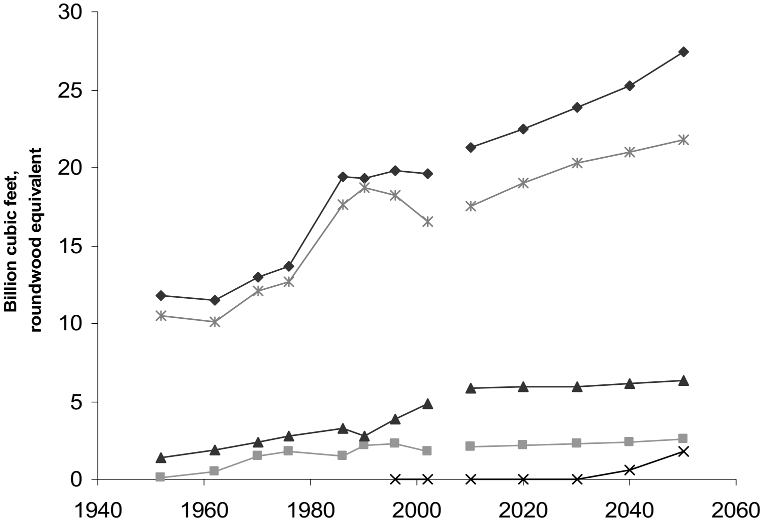

Figure 9-5. Total U.S. roundwood consumption (black diamond), harvest (gray star), imports (blank triangle), exports (gray box), and SRWC (black cross).

4.2 Policy analysis

In the context of assessment, the original policy interest was to identify policy needs in terms of impacts to prices rather than shortfalls in quantity. This price-based approach appealed to policy makers interested in price changes and estimates of consumer or producer impacts. Use of empirical policy tools also increased the ability to differentiate regional and national market impacts of changes in supply from one ownership in one region. Early applications (see Adams et al. 1976) involved potential responses of softwood markets to reductions in federal timber flows that would especially impact western producers. In this case, lumber and stumpage prices would rise, increasing harvests from private timberlands and lumber imports from Canada. Stumpage prices would increase the most on the west coast,

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[14] Domestic forest harvest rises by 5.3 bcf and SRWC by 1.8 bcf.

accentuating the concentration of lumber and plywood production in the South.

These latter results demonstrated the broad market impacts of what had been characterized as relatively local or regional policy issues. Similar results (see Haynes and Adams 1979) for impacts of expanded wilderness withdrawals demonstrated that changes in availability of public timber in the west did not lead to drastic changes in timber prices. Rather, increased production from private lands, mostly in the South, and increased softwood lumber imports from Canada greatly reduced potential price impacts associated with policy changes. These results were quickly adopted in ensuing policy discussions, and were reaffirmed in the early 1990s, following reductions in federal harvests in the west for habitat conservation. Prices in the 1900s and after clearly demonstrate a step up, and do not return to levels observed in the 1980s and earlier periods. The loss of public timber did lead to a substitution—so no famine—but it did not happen without cost. If private and Canadian timber had been cheaper before the drop in public cut, they would have been used instead of the public timber. But they were not cheaper, and the price of attracting them into the market after the drop in public cut was a step up in prices. Figure 9-6 shows the interesting price behavior associated with these changes.

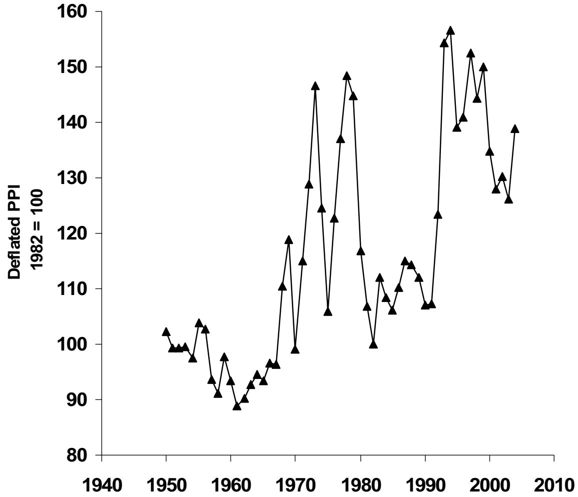

Figure 9-6. Changes in lumber producer price index.

Response of market-based supply in these policy debates stimulated interest in understanding the nature of market incentives for private landowners to increase forest stewardship. A survey in the late 1970s had identified a number of treatment opportunities on private timberlands, which, in spite of forecasts of rising prices, were not implemented. This led to a policy discussion about the need for tree-planting incentives. Results of economic models showed that incentives, which increased the extent of tree plantations in the near term, would lead to increased inventories in two decades, reducing stumpage prices in the South, and elsewhere reducing financial returns of practices already implemented and lowering incentives for further forest stewardship. This dynamic link between actions now and impacts in the future was also an issue in the estimation of economic effects associated with growth slowdowns expected to result from increased forest declines caused by acid rain or other air pollutants (see Haynes and Kaiser 1990). The proponents for taking action thought economic effects should occur at the same pace as reductions in growth. The use of the models demonstrated, however, that economic impacts evolved over several decades as a function of slower growth in inventory levels and consequently harvests.

Table 9-2. Indices of changes for selected indicators for the United States, developed from data summarized in Table 23 in Haynes (2003)

	Criterion 1			Criterion 2			Criterion 6
Year	Extent of softwood area	Extent of older stands	Fragmen-tation	Area of timber land	Total growing stock inventory	Ratio of growth to harvest	Total harvest
	Percent of total	1976= 100	1952= 100	1952= 100	1952= 100	Percent	
1952	70		100	100	100	128	100
1962	68		89	99	108	161	95
1970	66		97	97	114	164	111
1976	64	100	96	95	119	171	118
1986	59	76	124	96	124	125	162
1991	57	74	124	99	128	121	164
2000	58	67	110	99	136	144	151
2010	58	66	108	98	153	140	167
2020	60	65	107	97	166	130	181
2030	61	65	106	97	177	123	193
2040	62	65	105	96	186	117	202
2050	62	65	105	96	193	110	212

Recently, strategic discussions of broad-scale forest policies are being set in the context of whether we can sustain[15] forest resources despite increasing consumption of forest products. Both historic and projected trends are

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[15] The United States adopted the Montreal Process to facilitate a discussion of indicators for sustainable forest management (for a list see http: www.fs.fed.us/land/sustain_dev/sd/welcome.htm).

illustrated in Table 9-2 for direct and indirect or proxy measures of selected national data (converted to indices to make them comparable and grouped by criterion). The historic trends illustrate that there was a general decline in some indicators characterizing conservation of biological diversity (criterion 1) and maintenance of productive capacity (criterion 2), but that this decline slowed in the 1990s, and is expected to stabilize in the future. At the same time, timber harvest (one indicator of socioeconomic benefits [criterion 6]) increased, peaking in the late 1980s. These trends suggest that, while in the period 1950-1980s there were tradeoffs between ecological conditions and economic growth, changes in public attitudes, improving forest management, and increased productivity of forestlands resulted in greater balance by the 1990s. While trade is not an indicator in the Montreal framework, net trade increased threefold (see Figure 9-1) during the 1990s enabling Americans to maintain their consumption, reduce federal harvests in the west, and improve forest conditions. The various indicators also suggest that we are seeing an aging of forests as production effectively shifts to fewer timberland acres. Overall, timber types remain relatively stable after some initial declines in the 1950s and 1960s. The results also show that, while fragmentation has emerged as a critical natural resource issue, the contribution that harvest area makes to fragmentation is expected to decline. Finally, these results have positive implications for the contribution of U.S. forests to global carbon cycles (criterion 5). In general, U.S. forest management has resulted in increasing total levels of carbon storage, given that inventory levels are expected to increase by 42% over the next 50 years.

4.3 Scenario planning: the use of TAMM, ATLAS, NAPAP, and AREACHANGE as an integrated system for strategic planning

There has been an evolution in the use of computer-based models in strategic planning by both government and non-government organizations. This is particularly evident in the use of simulation techniques to analyze alternative futures and management strategies to better inform land managers and the public. This approach, called scenario planning (Wack 1985), has been a part of RPA efforts since 1983 (USDA FS 1982, Haynes 1990, Haynes et al. 1995). These applications take a classical approach to sensitivity analysis, in which a limited number of key exogenous and endogenous elements were varied and key projection results were examined for differences. These differences allow the identification of emerging problems, and provide a way to measure the effectiveness of possible solutions to various problems.

The use of scenario analysis has added depth to the use of the bioeconomic models for policy analysis. In the latter application, the models have been used to examine the effectiveness of specific policy actions such as tariff increase or regional federal timber harvest decease. But the experience gained from examining the differences and similarities across scenarios has helped shape qualitative notions of the key uncertainties in the outlook and how the forest sector adjusts and adapts limiting the economic effects of changes in external conditions.

Examining alternative futures has shaped the perceptions of land managers and policy makers, eventually leading to better decisions. They have been useful in communicating the links between various assumptions and possible outcomes. Using scenario planning has not resulted in less acrimonious debate or less controversy, but these debates have been better informed. There are also instances in which the planning process itself led to more intense controversy by exposing the importance of underlying processes that were themselves controversial.

5. CLOSING

The U.S. experience with using bioeconomic models for broad-scale assessments and policy analysis offers a number of lessons. Key is that the use of integrated assessments increases the effectiveness of generalized approaches to planning or risk assessments. The demonstration of this was the application of bioeconomic models to the full spectrum of policy issues in the last quarter century.

Use of computer-based forest-sector models has lead to several unique economic insights. These include the extent and consequence of how private timberland owners respond (based on their objectives), both in terms of harvest and land-management intensity, to changes in prices and land values; increased environmental regulations often increase timber costs, shifting production to cheaper producers both in that region or country and elsewhere; and the models have been helpful in synthesizing information for policy development.

These models have influenced contemporary thinking about the need and way to consider the uncertainties associated with various policies. The ability to use scenario-planning approaches has facilitated strategic planning by providing policy makers with information necessary for decision making without knowledge about their welfare preferences or particular targets. These approaches also shifted the focus from forecasting the future to looking at a set of plausible futures, each dependent on the assumptions that underlie that future. By doing so, the technique focuses on what might happen, or go wrong, and how to deal with it.

Finally, using a computer-based bioeconomic model has lead to more enduring decisions and policies by allowing decision makers to explore management options in much greater detail, as required by the increasing complexity of debates surrounding forest policies. These models, with their deliberate approach to policy analysis, can provide powerful tools and inform the debate. Models, however, do not operate in a vacuum, and by themselves will not lead to better policies. Successful application of management sciences to policy depends on the effectiveness of individuals to be advocates for their use in exploring specific policy questions.

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PART III

SYNTHETIC APPLICATIONS

Chapter 10

DIGITAL FORESTRY IN THE WILDLAND-URBAN INTERFACE*

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Abstract: Growing human populations have led to the expansion of the Wildland-Urban Interface (WUI) across the southeastern United States. The juxtaposition of buildings, infrastructure, and forests in the WUI creates challenges for natural resource managers. The presence of flammable vegetation, high rates of human-caused ignitions and high building densities combine to increase risks of catastrophic loss from wildfire in the WUI. At the same time, fragmentation of large ownerships into smaller parcels and changing demographics may limit the possibilities for managing fuels with prescribed fire. To make effective decisions in this environment, land managers will need to integrate a large volume of information characterizing the physical features, biological characteristics, and human dimensions of these landscapes. Remote sensing and Geographic Information Systems (GIS) technologies are crucial in this regard, but they must also be integrated with field surveys, fire behavior models, and decision-support tools to carry out risk assessments and develop management plans for the WUI. This chapter outlines the types of geospatial datasets that are currently available to map fuels and fire risk, provides examples of how GIS has been applied in the WUI, and suggests future directions for the integration of GIS datasets and spatial models to support forest management in the WUI.

Key words: Wildland-Urban Interface (WUI); Geographic Information Systems (GIS); spatial modeling; wildfire risk; fuel reduction; prescribed fire.

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1. INTRODUCTION

Changing human demographics have altered landscape patterns and created new challenges for forest management in the southeastern United States. Sprawling development at the peripheries of urban areas and increasing population densities in rural areas have expanded the Wildland-Urban Interface (WUI), where homes and other buildings are adjacent to, or intermixed with, flammable vegetation. These new land-use patterns have created challenges for natural-resource managers, whose job is to sustain timber production, wildlife habitat, and water quality in forested areas while protecting homes, infrastructure, and natural resources from fire. Historically, prescribed understory burning was widely used to reduce fuel loads and fire risk, while maintaining critical ecological processes in the South's fire-adapted ecosystems. However, concerns over safety and liability related to smoke and escaped fires can limit the applicability of prescribed fire in the WUI. Alternative strategies for mitigating wildfire damage include mechanical or chemical fuel-reduction treatments, as well as educational programs aimed at helping homeowners develop fire-resistant landscapes.

A simple map of WUI boundaries would provide useful guidance for managers, who must designate appropriate fuel-reduction treatments for different locations, and prioritize these treatments to reduce fire risk. However, heterogeneous patterns of both forest cover and human settlement across the South belie this characterization of the WUI as a static and discrete management unit. Instead, it is more realistic to conceptualize the WUI as a dynamic set of social, physical, and biotic gradients. Computer technology is a valuable asset to managers, who must integrate large volumes of information to make decisions in this spatially and temporally variable environment (Figure 10-1). Global positioning system (GPS) technology and remotely sensed imagery can be used to map vegetation and fuels as well as physical and anthropogenic features. Geographic information systems (GIS) provide the framework for storing, manipulating, and analyzing this spatial information. Computer simulation models of fire behavior and vegetation dynamics can be applied to project changes through time and evaluate the consequences of alternative management scenarios.

In this chapter, we focus on the problem of fuel management in the southeastern United States as a case study for exploring the digital forestry paradigm (Zhao et al. 2005). At the national level, a major goal of the National Fire Plan is to facilitate the application of fuel-reduction treatments for mitigating the hazard of uncharacteristic wildfire. The application of geospatial technologies to map vegetation and fuels, predict fire behavior and effects, and model the effectiveness of various strategies for fuel management has emerged as a cornerstone of these efforts. We recognize that the challenge of managing the WUI encompasses more than just fuel management. Other important concerns include the impacts of land-use change on wildlife habitat, the introduction of exotic species, and the influences of ownership changes and parcelization on timber supply (Macie and Hermansen 2002). Our goal here is not to provide a comprehensive review of management issues related to the WUI, but instead to highlight examples of how multiple digital information technologies can be integrated to support fuel management and fire-hazard reduction. The strengths and weaknesses of existing approaches are discussed, and suggestions for expanded implementation of digital forestry are provided.

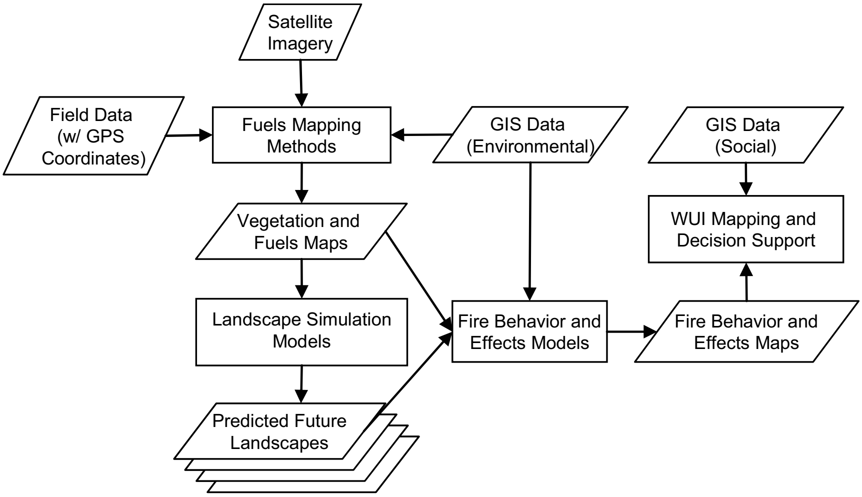

Figure 10-1. Flowchart illustrating the integration of multiple digital datasets and models for fire risk assessment and fire management in the Wildland Urban Interface.

2. DEFINING THE PROBLEM

In the United States, the popular conception of forest fires often focuses on large conflagrations in the western states. However, wildfire is also a common occurrence in the Southeast, where vegetation growth and fuel accumulation are rapid and ignitions from both lightning and humans are frequent. Fires in the Southeast have the potential to develop into large, dangerous conflagrations, as epitomized by the Volusia fire (111,130 acres) and the Flagler/St. John fire (94,656 acres), both of which occurred in Florida in 1998. Even though the annual wildfire acreage is relatively small compared to the western United States, the high density of homes and other structures across most of the Southeast result in a high potential for wildfire-related losses (Monroe 2002). High population densities increase the possibility of smoke-related health problems, even in areas that are far removed from the actual flames (Fowler 2003). The spatial juxtaposition of buildings and vegetation can create a conundrum for firefighters; homes must be protected, but the diversion of resources to defend structures can allow a fire to grow and threaten larger areas. Given these myriad challenges, it is not surprising that the present-day policies are focused on fires in the "intermix," or WUI (Pyne et al. 1996).

Fuel reduction is currently a major focus of fire management in the WUI. Unlike weather and terrain, the two other components of the fire behavior triangle, fuels can be modified through prescribed burning or mechanical treatments. Prescribed burning is often the preferred method for fuel management, because it is inexpensive compared to alternative mechanical treatments, and is particularly effective at reducing the fine surface fuels that have the greatest influence on fire behavior. However, the use of prescribed burning in the WUI can be constrained by negative public perceptions, potential risk of escaped fire, and air-quality and smoke-management regulations and health issues (Haines et al. 2001). Mechanical and chemical alternatives to prescribed burning are available, but these are usually more expensive, and may actually cause short-term increases in levels of fine fuels and the potential for extreme fire behavior (Brose and Wade 2002).

The potential for applying prescribed fire as a fuel-reduction treatment also depends on disturbance history and current stand conditions. In the absence of fire, autogenic succession in most southern pine forests leads to late-successional communities dominated by hardwoods. Fuel loads increase as succession progresses, but also shift from pyrogenic grasses and pine litter to less-flammable hardwood fuels (Maliakal et al. 2000). Increased overstory cover provides shelter from solar radiation and wind, leading to higher levels of understory fuel moisture (Streng and Harcombe 1982). Thus, it can be difficult to reintroduce fire into long-unburned stands under weather conditions considered acceptable for prescribed burning (Menges and Hawkes 1998). Fire-excluded stands can still carry fire, when fuel moisture is low enough, but burning under these conditions can result in extreme fire behavior and high levels of overstory tree mortality (Plocher 1999). In these cases, some type of mechanical fuel treatment will be needed before fire can be reintroduced.

Fire management in the Southeast, however, encompasses much more than just fire prevention and fuel reduction. Prior to European settlement, fire regimes, dominated by frequent, low-severity surface fires, created relatively open forests, ranging from pine savannahs of the Coastal Plain to hardwood-dominated forests in the Piedmont and the Southern Appalachians (Cowell 1995, Black et al. 2002). Fires resulted from a mixture of lightning and human ignitions, with mean fire return intervals ranging from less than 5 years in coastal plain pine forests plain to several decades in the Piedmont and the Southern Appalachians (Wade et al. 2000). The important role of fire in these ecosystems is evidenced by the large number of fire-adapted trees, including longleaf pine (*Pinus palustris*), and many native oaks (*Quercus* spp.). Frequent surface fires also foster diverse understory plant communities (Kirkman et al. 2001) and provide open habitat for endangered species such as the red-cockaded woodpecker (*Picoides borealis*) (James et et al. 2001). Thus, the overarching challenge for fuels and fire management in the Southeast is to sustain the role of fire as an ecosystem process, while at the same time minimizing the risk of uncontrolled wildfire, and the negative impacts of smoke.

3. APPLICATIONS OF DIGITAL FORESTRY CONCEPTS

3.1 Mapping vegetation and fuels

Information about the quantity and quality of fuels is necessary for predicting fire behavior, and evaluating potential fire effects. When assessments are expanded to large landscapes, the spatial configuration of the fuel mosaic must also be considered. Spatial patterns of fuels, topography, and wind all interact to influence fire spread and intensity. Fuels are of particular interest from a management perspective, because they can be modified through mechanical treatments or prescribed burning. Fuel maps can provide valuable information about the total amount of land in need of fuel-reduction treatments, as well as the locations of major areas of fuel accumulation.

Aerial photography and satellite remote sensing have proved to be effective technologies for mapping forest vegetation at landscape to regional scales. However, the mapping of forest fuels presents greater challenges than general land-cover classifications. For predicting potential surface-fire behavior, the most important fuels include leaf litter, dead branches, and the foliage of live shrubs, grasses, and herbaceous plants. These surface fuels have traditionally been classified into a small number of stylized fuel models (Anderson 1982), although new and expanded classification systems have recently been developed (Sandberg et al. 2001, Scott and Burgan 2005). Surface fuels are often hidden beneath the forest canopy, and may be too fine grained to discern from remote imagery, even if the understory is visible. Because of these problems, surface fuels are usually mapped indirectly, based on assumed relationships with one or more overstory attributes that can be inferred from image texture or spectral signatures. For example, fuel loadings may vary with stand age and overstory basal area (Wade et al. 2000), or differ among major forest-cover types (Hely et al. 2000). When using this approach, the application of GPS technology is critical for linking field-based assessments of understory fuels with imagery and GIS databases.

Remotely sensed imagery, acquired from aircraft and satellites, has been used to map surface fuels in a variety of landscapes. Oswald et al. (2000) mapped surface-fuel models in East Texas by interpreting aerial photographs, and predicting fuel models based on percent pine composition, pine basal area, and crown closure. Similarly, Welch et al. (2002) developed a fuel map for the Great Smokey Mountains National Park by linking surface-fuel models to 25 generalized overstory vegetation classes that were interpreted from aerial photographs. Brandis and Jacobsen (2003) mapped surface-fuel loads in New South Wales, Australia, based on characteristics of the forest canopy obtained from Landsat TM imagery. They applied models of litterfall and decomposition to translate estimates of canopy biomass into steady-state fine fuel loadings. Van Wagtendonk and Root (2003) mapped vegetation classes and associated surface-fuel models in Yosemite National Park using seasonal trends in Normalized Difference Vegetation Index (NDVI) measured with Landsat TM.

An alternative to traditional aerial photo interpretation or image classification is the predictive vegetation-mapping approach (Franklin 1995). Statistical models are used to predict vegetation characteristics using a combination of remotely sensed imagery and GIS layers describing climate, topography, and other biophysical variables. The incorporation of additional information, in the form of GIS datasets, is generally believed to improve mapping accuracy beyond that obtained with remote-sensing imagery alone. Rollins et al. (2004) mapped surface-fuel models in the Kootenai River Basin of northwestern Montana using Landsat TM bands, a digital elevation model (DEM), and climate maps. Reich et al. (2004) mapped surface-fuel loadings in the Black Hills of South Dakota using Landsat TM bands, a DEM, and a forest-cover type map. Falkowski et al. (2005) mapped surface-fuel models in northwest Idaho, based on structural stages, cover types, and potential vegetation types derived from ASTER imagery and topographic variables.

For predicting the risk of crown fires, maps of canopy variables, such as canopy bulk density and height to the base of the live canopy, are needed (Scott and Reinhardt 2001). Canopy closure and stand height are also necessary to model reductions in wind speed caused by the forest canopy. Compared to surface fuels, these canopy variables have a more direct influence on the spectral response of the forest overstory. Canopy bulk density is correlated with leaf-area index (LAI), and has been mapped using Landsat TM imagery (Perry et al. 2004), and ASTER imagery (Falkowski et al. 2005). However, spectral vegetation indices are insensitive to LAI variability in dense, closed-canopy stands (Asner et al. 2003), and are likely to exhibit a similar response to canopy bulk density. Estimates of tree height and height to base of the live canopy must be indirectly derived from spectral variability related to overstory canopy structure (Lefsky and Cohen 2003). Active remote sensing technologies such as sensors for light detection and ranging (LIDAR) hold particular promise for improved mapping of three-dimensional canopy structure. LIDAR has been used to measure canopy attributes such as volume, mass, bulk density, and height to base in loblolly pine forests in Texas (Roberts et al. 2005), pine forests in central Spain (Riano et al. 2004), and Douglas-fir forests in the Pacific Northwest, USA (Andersen et al. 2005).

A major challenge in fuel mapping is the need for consistent estimation of multiple variables, while maintaining a realistic correlation structure. For example, a spatial model of fire effects might require maps of fuel models, stand height, and canopy closure to predict behavior of surface fire, along with maps of tree species and sizes to predict vegetation responses. Keane et al. (2000) dealt with this problem by using a classification approach. They first defined strata by overlaying potential vegetation classes derived from terrain modeling with cover types and structural stages derived from Landsat TM imagery. A look-up table was then used to assign representative canopy variables and surface-fuel models to each stratum. Wimberly et al. (2003) used the Gradient Nearest Neighbor (GNN) method (Ohmann and Gregory 2002) to simultaneously predict multiple vegetation attributes and fuel variables in Coastal Oregon based on Landsat imagery and environmental variables. This approach combined a multivariate predictive model (Canonical Correspondence Analysis) with imputation of forest inventory data to assign representative plots to all locations in the landscape.

3.2 Delineating the wildland-urban interface

The intermingling of humans and natural systems in the WUI affects a variety of resource values, including water quality, wildlife habitat, and timber production. A topic of particular concern is the heightened risk of high-severity wildfire in the WUI. In this context, risk encompasses both the probability of an unwanted occurrence (wildfire), and the potential consequences of its occurrence (ecological degradation or loss of property and lives). Although fuel maps can be used to identify areas of high fuel accumulation, sufficient resources are usually not available to apply fuel-reduction treatments to all of these areas. Additional information on the locations of objects at risk, such as people and buildings, is needed to identify where fuel-reduction treatments will lead to the greatest reduction in fire risk. If arson or accidental ignitions are major sources of wildfire, humans can also impose a feedback loop that increases wildfire probability in the WUI (Cardille et al. 2001).

The U.S. Census is the major source of spatial information on human demographics in the United States (Peters and MacDonald 2004). Similar datasets are available for many other countries. The spatial units of the census are mapped at 1:100,000 scale, and are organized in a nested spatial hierarchy, comprised of blocks, block groups, tracts, and counties in order of increasing size. These units are scaled to a target population size. For example, census blocks typically have a population of 85 people, and are therefore much larger in rural areas than in urban areas. At the block level, only limited information about population and household densities is released. At the block-group level and above, additional information on education, income, time of residence, and a variety of other demographic variables are available.

Census data are particularly useful for measuring low-density development in forested areas that can be difficult to detect using satellite imagery (Theobald 2001). However, the large sizes of census blocks in rural areas limits the spatial precision with which patterns of housing units can be mapped (Figure 10-2a). Furthermore, many types of buildings, such as schools, hospitals, and industrial facilities, are not included in the count of housing units. Although these types of buildings are likely to be correlated with housing density at very broad scales, they can not be identified from the census data at small scales. Thus, additional sources of spatial data on human populations will be necessary, when the goal is to develop more detailed, local assessments.

Another type of spatial information reflecting human demographics and land use is the pattern of roads. At regional scales, road densities are correlated with housing densities, and the intensity of human land use (Hawbaker et al. 2005). In rural areas, individual buildings are more likely to be located close to a road than far from one (Figure 10-2b). Furthermore, the roads themselves can have a strong effect on landscape structure, wildlife habitat, and probability of wildfire ignition (Forman 2002). The TIGER/Line files produced by the U.S. Census contain data on roads and other transportation networks for the entire United States at 1:100,000 scale. Road datasets at larger cartographic scales (1:24,000 or greater) provide higher spatial accuracy, and are often available through state or local agencies. Other potentially valuable spatial data for wildfire assessments in the WUI include maps of individual buildings, parcels (Figure 10-2c), utility lines, hospitals, schools, airports, or other features that could be affected fire or smoke. Typically, these types of GIS datasets are maintained by county and local governments, and are not readily available at a regional level. One relatively straightforward approach to mapping the WUI is to overlay land cover and census data using a rule-based approach. This method has been used to classify urban, interface, intermix, and wildland areas across the entire United States (Radeloff et al. 2005). Interface areas were identified using Boolean logic, based on a minimum housing density, a maximum vegetation cover, and a threshold distance to one or more large forested blocks. Intermix areas were classified based on minimum housing and vegetation densities. The results of this study emphasize the ubiquity of the WUI in the southeastern United States. Large percentages of the total land area in Alabama (24%), Georgia (26%), Tennessee (30%), South Carolina (34%), North Carolina (44%), and Virginia (34%) are classified as WUI. Percentages of housing units occurring in the WUI are even higher, ranging from 53% to 71% in the states listed above. However, there is considerable variability in ignition probabilities, fuel characteristics, and structure densities within these areas, and not all the lands classified as WUI are at high risk from wildfire. More detailed subregional analyses are needed to identify areas within the WUI where there is a significant threat of wildfire occurrence and resulting economic losses.

Maps of the WUI can be refined, if additional data on fuels, topography, and cultural features are available. The state of Florida used this approach in their Florida Fire Risk Assessment System (FRAS) (http://flame.fl-dof.com/risk/). A susceptibility index for wildland fire was mapped by predicting potential fire behavior, based on fuels, vegetation, topography, and historical weather, and overlaying these predictions with a map of historical fire locations. An index of fire effects was mapped by integrating spatial information on human populations, natural resources, and critical infrastructure elements with estimates of costs for fire suppression. These two indices were combined into a final map of fire risk. Zhang (2004) developed a generalized WUI index that combined GIS layers describing forest cover, household density, road density, slope, aspect, forest community type, and ownership. Landscape-level relationships were incorporated by using a 1-mile-radius moving window to summarize forest cover, housing, and roads. These methods were used to develop localized WUI maps for the southern Appalachian highlands along the northwestern boundary of Great Smoky Mountains National Park, and for the South Atlantic Coastal Plain in the vicinity of Tallahassee, FL (Zhang 2004).

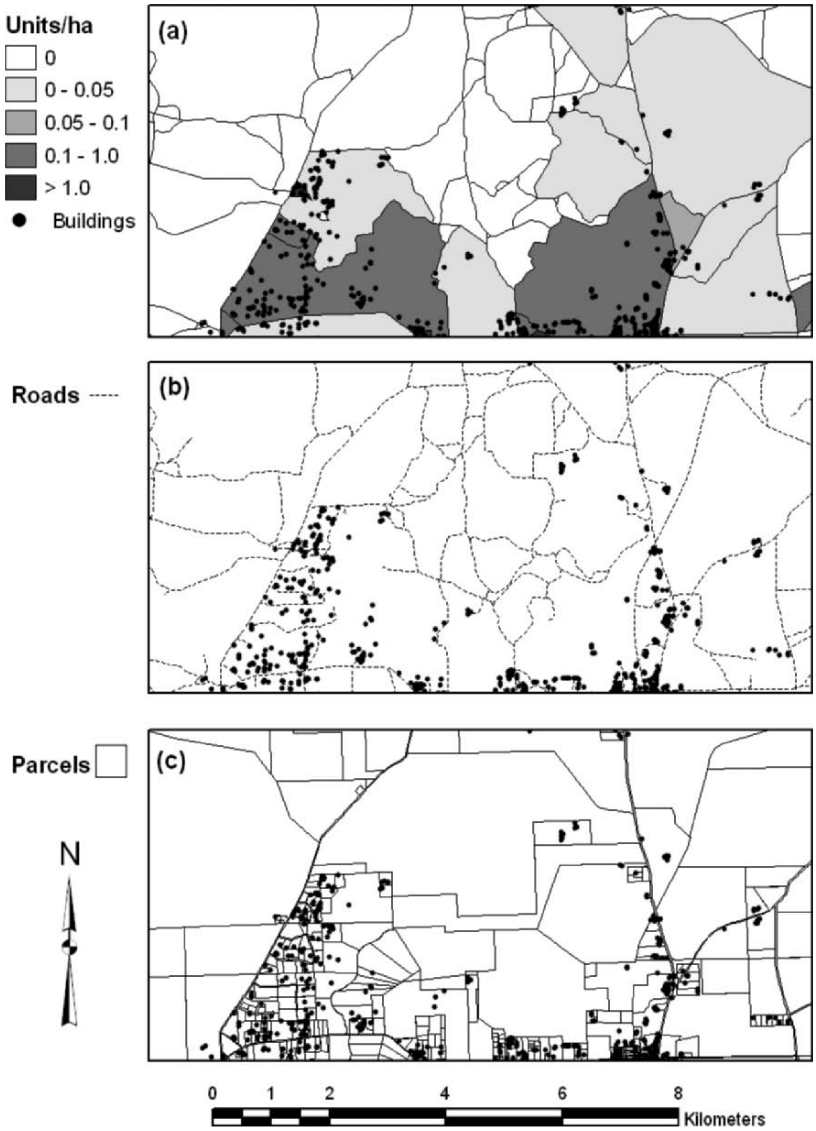

Figure 10-2. GIS datasets characterizing human habitation and infrastructure in northeastern Leon County, FL. a) Housing-unit density from the 2000 census at the block level; b) County-maintained roads; c) Parcel boundaries. Dots represent mapped building locations from 2003.

4. FUTURE DIRECTIONS

4.1 Uncertainty analysis

All maps derived from remote sensing have inherent error, usually expressed as a confusion matrix, in which ground-truth data are compared with predicted map classifications. Statistics derived from this confusion matrix include the percentage of observations correctly classified, along with errors of omission and commission. When continuous variables are mapped, predicted map values can be plotted against measured ground values, and the strength of the relationship assessed by the coefficient of determination. Reported accuracy levels for maps of surface fuels vary, ranging from 54.3% correctly classified for a map of 7 fuel models in Yosemite National Park (Van Wagtendonk and Root 2003) to 69.2% for a map of 3 fuel models in Kootenai River Basin (Rollins et al. 2004). In making this type of cross-study comparison, it should be noted that classification accuracy is expected to increase as the number of mapped classes decreases (Cohen et al. 1995).

The implications of this uncertainty for the use of maps in assessments of fire risk are not clear. Even if vegetation and fuels maps have considerable errors at the pixel or patch level, they may still be useful for generating aggregate predictions across larger land units. However, relatively small variations in map accuracy may translate into large changes in the spatial patterns represented in the map (Shao et al. 2001). Traditional error assessments of remote-sensing data products do not explicitly consider the spatial distribution of errors, although new methods for detailing spatial error are emerging (Plourde and Congalton 2003).

A particularly promising methodology uses geostatistics and stochastic simulation to generate a distribution of equally probable maps, given the observed level of map error. Viewing these multiple realizations of a map provides a way for users to visualize the amount and spatial pattern of uncertainty. A large sample of alternative maps can be generated and run through subsequent models and analyses in a Monte Carlo approach to quantify the impacts of error propagation on the conclusions drawn from a GIS analysis (Kyriakidis et al. 1999, Kyriakidis and Dungan 2001). It would be illuminating to carry out such an analysis with fuel maps and fire behavior models to assess the degree to which map error influences subsequent predictions of fire behavior and effects.

4.2 Enhanced mapping of the wildland-urban interface

Efforts at mapping the WUI to date have focused on combining spatial information on vegetation, fuels, and fire hazard with the geographic distribution of structures that are potentially at risk from fire. However, the WUI has much broader impacts on both ecological and social values than just fire risk. Some of these other factors may ultimately feed back and influence the potential for carrying out fuel-reduction treatments in the WUI. For example, objectives for habitat management for some species may conflict with the need to alter forest structure to reduce fire risk. GIS-based models for wildlife habitat (e.g., Liu et al. 1995, Cox and Engstrom 2001) have been developed for a wide range of species, and could be integrated with assessments of fire risk to gain a broader picture of potential impacts on natural resources resulting from wildland fire, or from treatments designed to reduce the risk of fire.

The same social forces that have created the WUI also limit the applicability of some management practices for reducing fire risk. For example, thinning of merchantable trees can lower canopy bulk density and reduce the risk of active crown fires (Agee and Skinner 2005). In the southern pine flatwood forests, commercial thinning also temporarily reduces the loadings of live and dead surface fuels (Brose and Wade 2002). However, as human populations increase, and forested ownerships are divided into smaller parcels, the potential for commercial timber harvesting decreases because of declining economies of scale, increased value of land for uses other than forestry, and changing landowner values and objectives. Analyses of forest inventory data from a number of southern states support this contention. Rates of timber harvest decline with decreasing tract sizes in Virginia (Thompson and Johnson 1996), South Carolina (Thompson 1997), and Florida (Thompson 1999).

Increasing population densities in the WUI also present challenges for use of prescribed fire as a management tool because of negative public perceptions, and potential liability resulting from smoke and escaped fire (Miller and Wade 2003). Air-quality regulations may result in restrictions on the use of prescribed fire in and around locations designated as federal non-attainment areas for particulate matter (Riebau and Fox 2001). These concerns make implementing prescribed burning and other types of fuel treatments more costly in the WUI than in more rural areas (Berry and Hesseln 2004), and will reduce and ultimately eliminate the use of prescribed fire in many areas as human populations increase. In the south-central United States, the frequency of prescribed burning decreased with increasing population density, and was lower on nonindustrial private forestlands than on public lands (Zhai et al. 2003). In Florida, the use of prescribed burning was also negatively related to population density, and more prevalent on public than private lands (Butry et al. 2002).

These types of management constraints can be modeled and displayed in a GIS context. As an example, we created a map of the potential for commercial timber harvest based on a study by Wear et al. (1999). Their research found that as human population density increased from 20 to 70 people per square mile, the probability of commercial timber harvest (PCH) decreased from approximately 75% to 25%. In this context, variability in population density is assumed to be correlated with several proximal factors that influence forest management including parcel size, land values, and landowner objectives. Results from this study were extrapolated across central Virginia by predicting PCH as a logistic function of population density at the census-block level. The percentage of forested land cover in each census block was also computed using the NLCD land cover dataset from the early 1990s (Vogelmann et al. 2001). A WUI index was then generated for each census by multiplying (1 – PCH) by the percentage of forested landcover within each census block (Figure 10-3).

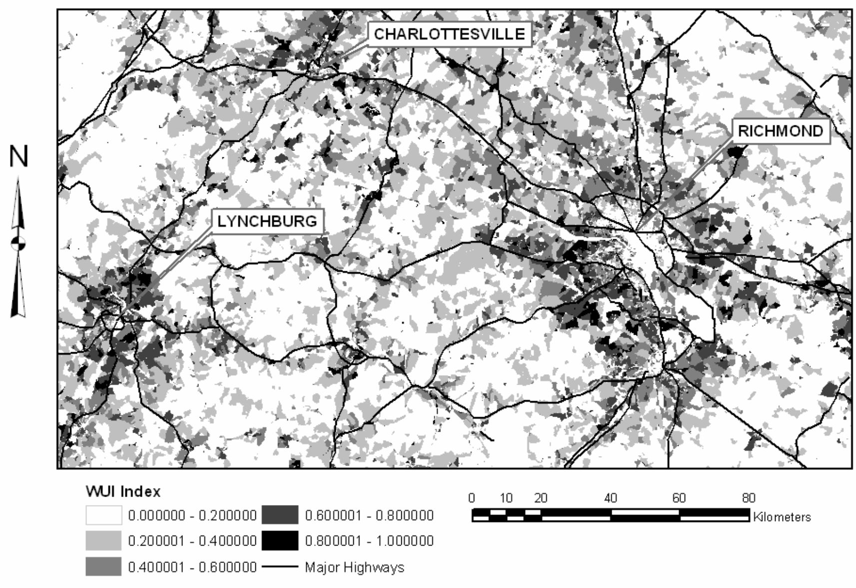

Figure 10-3. WUI index, reflecting potential constraints on commercial timber harvesting in central Virginia, and modeled as a function of forest cover and population density.

High values of the index identify areas where forest cover and fuels are abundant, but where fuel treatments linked to thinning or other silvicultural operations are unlikely to be commercially viable because of dense human populations. In contrast, low values of the index identify areas where forest cover is low (cities and agricultural areas), or forested rural areas where silvicultural activities are likely to occur. Not surprisingly, the highest index values are located on the outskirts of cities and along major transportation corridors – the same areas where structures are at greatest risk from wildfire and fuel-reduction treatments are most needed. This type of model can be refined, if additional spatial data on forest-tract size, transportation networks, and processing facilities are available. Similarly, maps of prescribed burning potential could be developed based on the spatial pattern of neighborhoods, roads, hospitals, and other smoke-sensitive areas.

4.3 Decision support

The ultimate step in applying the paradigm of digital forestry to the WUI is to link digital spatial databases with analytical tools for evaluating alternative strategies for fire management and fuel reduction. One approach is to use simulation models to study interactions between spread of fire and the spatial pattern of fuel treatments. Modeling studies in hypothetical landscapes can be used to derive general conclusions about treatment effectiveness. Experiments with a probabilistic cellular-automata-based model demonstrated that spread of fire could be greatly reduced by fuel treatments that comprised a relatively small proportion of the landscape, and that a regular pattern of fuel treatments was more effective than a random pattern (Loehle 2004). More sophisticated physically-based models of fire spread, such as FARSITE (Finney 1998), can account for spatial variability in fuels and terrain along with temporal variability in weather and fuel moisture. These types of models can also be applied in hypothetical landscapes to compare the effects of various treatment patterns on rates of spread and levels of fireline intensity (Finney 2001), or used to assess potential fire behavior in real landscapes, if geospatial datasets characterizing fuels, vegetation structure, and topography are available (Duncan and Schmalzer 2004, Stratton 2004).

Temporal as well as spatial patterns of fuel-reduction treatments must ultimately be considered in the development of effective strategies for fuels management. In the absence of fire, plant communities change through autogenic succession. These changes are typically accompanied by increased fuel loads as litter accumulates, and understory vegetation grows (Wade et al. 2000). Although prescribed fire can greatly reduce fine surface fuels and live understory biomass in southeastern forests (Brose and Wade 2002, Waldrop et al. 2004), fuel loads will recover rapidly without repeated burns. Natural disturbances, such as tornadoes, hurricanes, and insect outbreaks, can add to fuel loads and increase fire intensity (Liu et al. 1997). Mechanical treatments such as thinning reduce canopy bulk density, and decrease future litter and branch inputs, but can also temporarily increase fine fuel loads, if logging residue is left on site (Waldrop et al. 2004). Thus, fuel maps and models of fire behavior must ultimately be integrated with models of vegetation dynamics, fire effects, and other disturbance agents.

Several individual-tree-based models of forest dynamics have been extended to incorporate fuel loading and fire effects on forest vegetation (Keane et al. 1990, Miller and Urban 1999, Reinhardt and Crookston 2003). Changes in forest structure and composition are projected using equations that predict tree establishment, growth, and mortality, based on competitive interactions with other trees in a stand. Fire is incorporated by tracking fuel inputs from litterfall and tree mortality, fuel decomposition, fire intensity as a function of fuel loads, and fire-induced tree mortality as a function of fire intensity, tree species, and tree sizes. To scale up to the landscape level, patch-level models can be linked to polygon features within a GIS to reference spatially varying model inputs, and to allocate model projections to specific locations on the landscape (Keane et al. 1996, McCarter et al. 1998, Li et al. 2000).

An alternative approach to landscape modeling is to use a simpler, rule-based model to simulate vegetation transitions for individual cells within a raster GIS framework. An example of this type of model is LANDIS 3.7, which models forests as different-aged cohorts of species within each cell (He and Mladenoff 1999b). Flammability can be modeled as a simple function of time since the last fire and the local environment, or can be tracked more explicitly by modeling inputs to, and outputs from, broad fuel classes (He et al. 2004). These simplifications make simulations more efficient, and allow models like LANDIS to focus more explicitly on landscape-scale spatial processes such as seed dispersal, management activities, and fire spread (Gustafson and Crow 1999, He and Mladenoff 1999a, b).

Scientists and managers have only recently begun integrating these new geospatial datasets and models to address fire- and fuel-management problems at broad spatial and temporal scales. In most cases, they have applied a relatively straightforward simulation approach in which a small number of alternative scenarios are assessed through a modeling experiment. LANDIS has been applied to compare the effects of six forest management scenarios on risk of canopy fire (Gustafson et al. 2004), and to assess the influences of three fuel-reduction strategies on fuel loads and probability of burning in the Missouri Ozarks (Shang et al. 2004). A project to assess fire risk in the southern Oregon Cascades linked a geospatial database with stand-level forest-growth simulations, landscape-level fire initiation, and fire spread models to compare potential burned areas and other ecological criteria between two management scenarios (Roloff et al. 2005).

Although these types of simulation experiments allow comparison of treatments, their results are constrained by the small number of scenarios typically chosen for study. In most cases, there are other, more effective solutions to problems in forest planning. Modeling frameworks have been proposed for optimizing the placement of fuel treatments on a landscape to minimize the risk of large, destructive fires (Hof and Omi 2003). However, solving these problems, using traditional optimization techniques such as linear or integer programming, is not feasible when spatial relationships and processes must be incorporated at the landscape level. The development and application of models for landscape planning to derive optimal strategies for fuel treatment represents an important area of ongoing research in the arena of digital forestry. The SafeD model, for example, used a hybrid optimization and simulation approach that integrated computer-intensive heuristic optimization algorithms with GIS databases and models of fire spread and forest dynamics (Graetz 2000, Bettinger et al. 2004). Similar modeling approaches have been used to evaluate the effectiveness of fuelbreaks (Sessions et al. 1999), and are being developed to perform spatial optimization for location of fuel treatments (Finney 2004, Kim and Bettinger 2005).

5. CONCLUSIONS

The WUI presents a complex tableau in which the need for reducing fire risk must be balanced against a wide range of other social, economic, and ecological constraints. A major goal in managing the WUI is deciding how how to best allocate limited resources for fuel management and reduction of fire hazard. Effective planning will require the integration of large quantities of digital information from a variety of sources (e.g. fuel plots, remotely sensed imagery, DEM) with landscape simulation models and decision support tools. This information will also need to be shared by different administrative units working across multiple spatial scales. Although digital forestry offers promise for meeting these needs, there are still significant challenges that need to be addressed. The vegetation classes that can be readily mapped using remotely-sensed imagery will not necessarily meet the information needs of managers applying fuel treatments on the ground. Similarly, broad-scale, strategic assessments of the WUI that are valuable at a national level will not provide the amount of detail necessary to predict wildfire hazards and support management decisions at the local level. The geospatial datasets and simulation models used in these assessments contain varying levels of uncertainty, and the implications of these uncertainties for decision-support applications are not well understood. Future natural resource managers must be able to critically assess these data sources and model outputs to make effective decisions. Training in the conceptual and methodological aspects of digital forestry will therefore be critical in helping the next generation of natural-resource professionals to meet these challenges.

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Chapter 11

LINKING MULTIPLE TOOLS: AN AMERICAN CASE[*]

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Abstract: This chapter introduces a digital system that links a number of computer tools including data collection, growth and yield simulations, a decision support system, and activity scheduling for sustainable forest management at Tillamook State Forest, Oregon, USA. To facilitate decision making by the Oregon Board of Forestry and the Oregon Department of Forestry (ODF), ODF, with support of the Oregon State University (OSU) Department of Forest Engineering, has developed a spatial harvest scheduling model to simultaneously schedule timber harvest, forest structure, and transportation at the landscape scale. A spatial model was required in order to represent ODF's planning goals that include the attainment of a distribution of floating patches of complex forest across the landscape. To prepare the data for scheduling a preliminary harvest plan over the entire forest with a supporting road network was developed. The solution algorithm uses simulated annealing to solve a Model II harvest scheduling model with spatial control. Post-processing tools have been developed to verify that the scheduling model is following the rules correctly and that the results are computationally correct.

Key words: Landscape planning; transportation planning; harvest scheduling; optimization; heuristics.

1. INTRODUCTION

Digital forestry is probably nowhere as prominent in modern forestry as in the application of forest landscape planning. In landscape planning it is necessary to envision how forest stands will develop across the landscape and how stands relate to each other on the landscape, now and into the future.

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Important functions of the landscape plan include the description of the intended forest structure across the landscape, a description of the budgets required to achieve the plan, anticipated physical outputs, and an easily understood interface to communicate results to interested audiences. The landscape plan also provides guidance for project activities. To develop a modern landscape plan requires the integration of graphic information systems, forest growth and yield models, and activity allocation systems. Forest landscape planning as it is known today was not possible before the advent of high speed digital computers, geographic information systems (GIS), modern assignment algorithms, and graphic interfaces.

2. PURPOSE OF THE PLAN

To facilitate decision making by the Oregon Board of Forestry and the Oregon Department of Forestry (ODF), with support of the OSU Department of Forest Engineering, ODF has developed a spatial harvest scheduling model to simultaneously schedule timber harvest, forest structure, and transportation at the landscape scale. This chapter briefly describes the structure of the model and illustrates the output.

Known within ODF as the Harvest and Habitat (H&H) Model, the model has been developed to simulate harvesting strategies for the approximately 632,000 acres of northwest forests managed under the Northwest & Southwest Oregon State Forests Management Plans by the State of Oregon. (Approximately 96% of these lands are managed by ODF on behalf of the Counties in which they are located, via a trust-like relationship; 4% of these lands are managed by ODF via agreement with the Oregon Department of State Lands.) Seven districts are involved, including the Tillamook, Forest Grove, Astoria, Western Lane, North Cascade, Southwest Oregon, and West Oregon districts. For purposes of our discussion here we refer to the Harvest and Habitat Model simply as the State model.

3. STRATEGIES, GOALS, AND CONSTRAINTS

The mandate for the management of Oregon state forests is to provide the greatest permanent value for the citizens of Oregon. To support the Oregon Board of Forestry in achieving that mandate, ODF has developed four major alternatives. Each alternative uses a different approach to reach its overall goal. The four alternatives (Table 11-1) are combinations of the Forest Management Plan (FMP), draft Habitat Conservation Plan (HCP), management without the FMP or the draft HCP but employing the Oregon

Forest Practices Act (FPA) standards used on private forest lands, and management using increased levels of reserves.

ODF conducts forest planning at three levels: strategic (the Forest Management Plan), tactical (10-year Implementation Plans) and operational (Annual Operation Plans). To be as realistic as possible, model construction and inputs use information from all three levels. However, ODF considers model outputs to be used primarily to address strategic-tactical questions, not project-specific operational questions. While modeling will provide useful information for operational questions, ODF's staff of professional foresters will continue to make the on-the-ground forest management decisions.

Table 11-1. Characteristics of the four planning alternatives

	Alternative #1: FMP and HCP	Alternative #2: FMP with no HCP	Alternative #3: Wood Emphasis	Alternative #4: Reserve-Based
General Description	FMP and HCP	FMP but no HCP	FPA standards; No FMP; No HCP; Emphasize timber production	50% of land in reserves; 50% managed per FMP
Timber Production & Structure Goals	Non-declining volume flow; 50% in complex structure; Maximize net present value	Non-declining volume flow; 50% in complex structure; Maximize net present value	Short rotations; Harvest oldest stands first; Maximize net present value; No structure goals	Non-declining flow on 50% of land; Reserve criteria on other 50%; 50% in complex structure outside reserves
Conservation Area Description	Habitat protection for threatened and endangered species (T&E)	Conduct surveys for T&E species before harvest; Set protection when found	Conduct surveys for T&E species before harvest; Set protection when found	50% land base in reserves; habitat protection for T&E species
Riparian Strategy Description	FMP riparian	FMP riparian	FPA riparian	Increased buffer widths over FMP riparian

The alternatives share some common sub goals including:

1. High net present value,
2. Non-declining flow of timber products,
3. Achievement of desired amounts of complex forest, and
4. Achievement of a desired distribution of complex forest structure patches on the landscape.

While achieving the goals, there are also a number of constraints:

1. Limit areas that can be cut in certain parts of the forest until the desired amount of complex forest is reached,
2. Limit areas that can be cut in certain parts of the forest for a number of time periods,
3. Limits on the contiguous area that can be clearcut in any one time period,
4. Require that a stand cannot have a final harvest immediately after a thinning,
5. Limit the maximum total area of regeneration harvest that can occur within a time period,
6. Require that thinning of upland parcels within a harvest unit must be coordinated, although they do not need to receive the same prescription. Also, if a riparian parcel within a harvest unit can be thinned, its timing must coincide with either the upland thinnings, or at a minimum be coordinated with the regeneration harvest of the uplands, providing the riparian parcel does not exceed a maximum age,
7. Limit on when recently thinned parcels can be re-entered,
8. Limit on the minimum age a harvest unit can have a regeneration harvest,
9. Limit on the maximum volume that travel over a road arc during a time period,
10. Specific requirements for stands with severe Swiss Needle Cast disease,
11. Require that stands with *Phellinus weirii*, a native fungus that causes laminated root rot, be assigned specific regeneration options for one rotation after the existing stand is harvested, and
12. Require that stands remain on the landscape for a minimum of 20 years after reaching older forest structure.

4. CHOICE OF DECISION UNIT

The goals and constraints define the necessary decision unit. From a tree management perspective, the stand is often considered the logical decision unit. This is because the stand represents a contiguous area which is assumed to be homogeneous in terms of its current state. However, existing stands may be too large to satisfy current forest practice rules and not recognize management opportunities and costs related to slope and aspect. Adopting stands as decision units also may not recognize subdivisions of stands that because of their spatial location are not eligible for the same set of management activities as other parts of the stand (i.e., owl circles, murrelet habitat, riparian zones) and must be managed in special ways to recognize wildlife or other management objectives. Spatial location is also needed to estimate transportation costs, both road construction and log transport. An additional consideration is the harvest unit. The harvest unit is a spatial unit that recognizes physical and economic considerations involved in implementing a silvicultural prescription. For the State model, the decision unit is termed the parcel. It is the smallest spatial area that is assumed to be homogeneous with respect to stand (vegetation), slope, aspect, riparian classification, harvest unit, watershed, as well as several other categories relating to management goals such as owl circles, murrelet habitat, and other specially designated areas that relate either recognize current condition or desired future condition. Parcels range in size from 0.01 ha to 48.5 ha with 65% of the area in parcels greater than 2 ha (Table 11-2). At solution time, harvesting treatments will be coordinated among parcels subject to the goals and constraints to become logical harvest units averaging about 20 ha. Parcels within the same harvest unit do not need to receive the same treatment, but treatments must occur at the same time. For example, when an upland parcel within a harvest unit is treated, a riparian parcel within the same harvest unit can be treated. However, if the upland parcel is not receiving a harvest, then the riparian parcel cannot be treated. Similarly, it is not required that all upland parcels within a harvest unit receive the same treatment, but the treatments must occur at the same time. For example, parcels on an east aspect within a harvest unit must be treated at the same time as those on a west aspect (i.e., thinned to different densities). The requirement for coordination of activities within harvest units recognizes the physical and economic linkages between harvest technology and topography in the Tillamook area.

Table 11-2. Distribution of parcels by size class

Parcel size (ha)	<0.4	0.4 - 2	2 - 12	12 +
Percent of area	8%	27%	54%	11%

5. PRESCRIPTION DEVELOPMENT AND DECISION VARIABLES

In order to reach the goals, a number of prescriptions have been developed for each stand type. These prescriptions represent various unique thinning pathways that either an existing stand type or a regenerated stand type could grow over time. Typically each of the 300-500 coniferous strata on each district has 50 to 100 unique thinning prescriptions developed for it. Hardwood stands have fewer options. Each stand type is grown forward in the Forest Vegetation Simulator (FVS) growth and yield model (Dixon 2003) for 150 years in five-year steps using an initial tree list from the forest inventory. FVS is a density dependent stand projection model. Various biological metrics, including a measure of stand structure, are evaluated at each 5-year period. The value (gross revenue without consideration of logging and transport costs) of the stand at each five-year point in time is calculated by considering species and log grade.

The purpose of the scheduling model is to assign a series of prescriptions and regeneration harvest times to each parcel to reach the goals while satisfying the constraints. For the State Forest problem as many as 2 million unique pathways can exist for an individual stand over the planning horizon. To avoid explicitly defining the pathways, 9 decision variables are defined for each parcel and the solution procedure evaluates the pathways implicitly rather than explicitly. The 9 decision variables are:

(1) The prescription assigned to the existing stand
(2) The period the harvest of the existing stand takes place, if at all
(3) The prescription assigned to the regenerated stand
(4) The period the regeneration harvest takes place, if at all
(5) The prescription assigned to the second regenerated stand
(6) The period the second regeneration harvest takes place, if at all
(7) The prescription assigned to the third regenerated stand
(8) The period the third regeneration harvest takes place, if at all
(9) The prescription assigned to the fourth regenerated stand.

6. MODEL STRUCTURE AND SOLUTION PROCEDURE

6.1 Model structure

The structure of the harvest scheduling model would be classified as a Model II (Johnson and Scheurman 1977). That is, stands that are harvested can switch prescriptions at regeneration time, and that the length of the rotation can also vary from rotation to rotation. Since the decision variables are integers, the resulting problem is a large integer programming problem. The Tillamook district has the largest model consisting of about 150,000 parcels or 1.35 million integer decision variables.

6.2 Solution procedure

To solve this problem, simulated annealing (Kirkpatrick et al. 1983), one of a family of well known modern heuristics to solve combinatorial optimization problems, is used (Reeves 1993, Glover and Kochenberger 2003). Simulated annealing is a stochastic, neighborhood search technique that builds up a solution incrementally by randomly selecting harvest units, prescriptions, and regeneration times for the parcels within the harvest unit. The algorithm includes rules to escape from local minima. The first application of simulated annealing to spatial harvest scheduling appears to have been done by Lockwood and Moore (1993). Since that time, simulated annealing has been applied to a number of harvest scheduling problems (Nelson and Liu 1994, Murray and Church 1995, Ohman and Eriksson 1998, Boston and Bettinger 1999, Van Deusen 1999, and Sessions et al. 2000).

In this application, the multiple goals are expressed as a goal programming problem objective function structure. Goal programming objective functions have been found useful in multi-criteria problems where feasible solutions may not exist in the sense of being able to meet all constraints. In order to evaluate the contribution to net present value, harvest and road costs are calculated based on the vegetation condition and spatial location of the harvest unit and its position on the transportation tree similar to the procedure used by Murray and Church (1995). Roads are constructed or reconstructed as necessary to support the harvest scheduling choices. For each move, spatial feasibility, i.e., clearcut size is checked before evaluation of the objective function. If a move survives the spatial feasibility test, its contribution to the objective function is calculated. A goal unique to ODF is reaching a target distribution of patches of complex forest of differing size floating across the landscape (Bordelon et al. 2000). This accounting problem is dealt with by tracking as many as 500 patches across 30 time periods or about 15,000 patches.

Solution time depends upon the number of polygons, but a “good” solution can be achieved within one hour on a 3.4 gigahertz computer with 1 gigabyte of RAM. Usually a number of runs must be made in order to fine tune the penalty functions being used in the goal programming objective function. Since the simulated annealing heuristic is stochastic, i.e., random numbers are used during the search process, multiple runs are made to identify dominant solutions for a given set of penalty weights.

7. ORGANIZATION AND INFORMATION FLOW

7.1 Organization

The H&H Project Plan defined the goals, objectives and key expectations including roles and responsibilities. ODF developed a hierarchy of teams to define goals, to translate goals into quantifiable objectives, and to provide liaison with external stakeholders. The Core Team was a group of field and staff specialists charged with ensuring that the overall goals and objectives of the project were met. The Policy Team was upper level decision-makers from ODF, the legislature, other state agencies and the Counties. Other technical specialists within ODF, other state agencies, OSU, and private consultants provided technical support. Focused interest groups were solicited to provide assistance with assumptions for specific alternatives and public meetings were held to review and comment on interim model results. The project's objective was to have a strong involvement from field personnel and staff specialists and ensure that the model outputs were field verified, implementable and consistent with the FMP. To ensure that the model outputs have district support, subcommittees of foresters and other specialists were used to develop many of the model input elements and model rules. Subcommittees developed vegetation data and prescriptions, transportation data, landscape rules, habitat evaluation as well as the tools to verify the model solution.

7.2 Information flow

The flow of information begins with the development of data layers that are necessary to provide the input for the scheduling model (Figure 11-1). The data, goals and constraints flow into the harvest scheduling model. Output from the harvest scheduling model is then verified through GIS and database tools to ensure that the treatment assignments are legitimate and that constraints are being satisfied. This is followed by District review to assess whether the solutions are implementable and whether operational realities have been reflected. If needed, data corrections and constraint modifications are made and the process repeated.

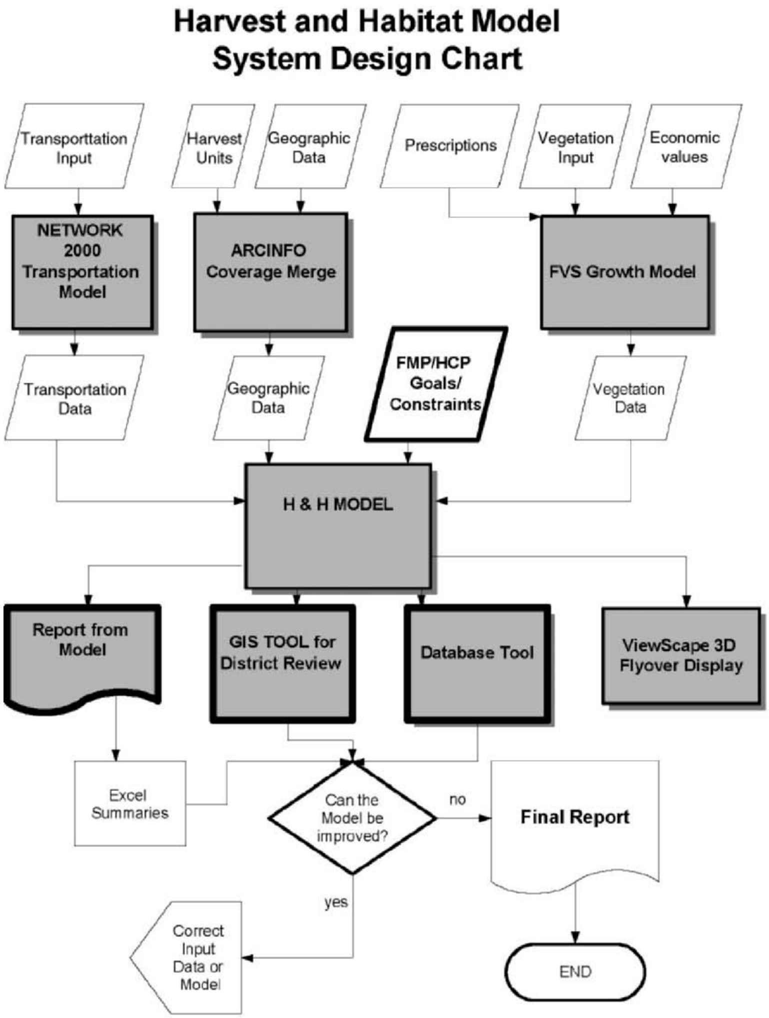

Figure 11-1. System design chart for the Harvest and Habitat land allocation and activity scheduling model.

Data layers include geographic data, vegetation data, harvest system units and transportation routes. The vegetation layer, derived from a combination of ground survey plots and aerial photo interpretation, includes species, diameter, height, and crown ratio (Figure 11-2).

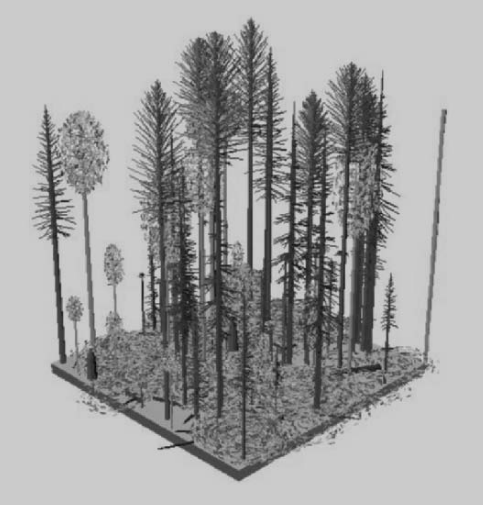

Figure 11-2. Graphical representation of a vegetation inventory plot using the SVS software (0.1 ha shown, 30 m ht pole) (McGaughey 1997).

Specific elements to be included in the model were a logging plan with a digital transportation system and logging units and vegetation data that used the latest stand level inventory projected with comprehensive silvicultural prescriptions.

In order to simulate the harvesting strategies, a preliminary logging plan has been prepared for the entire area; about 15,000 harvest units (Figure 11-3) (Plate 11-3). The harvest unit layer is an important data layer in mountainous terrain. It connects topography, harvesting technology, and road transportation. Parcels within harvest units need not receive the same silvicultural prescription, but the scheduling rules require that silvicultural treatments within harvest units have the same timing choices to recognize operational efficiency. The harvest units are aggregations of parcels that are homogeneous with respect to (a) management basin, (b) ownership, (c) site, and (d) logging system. In addition, parcels have other attributes including timber stand, riparian areas, and various kinds of fish and wildlife designations such as owl, murrelet, and salmon protection which are used to identify various types of harvest restrictions. At the landscape level, a structural classification (i.e., regeneration, closed single canopy, under story initiation, layered, old forest) is assigned to the harvest unit based on the structural classification of the parcels within the harvest unit. The harvest-unit structural classification is used to interpret and control the distribution of patches of complex forest (layered and old forest structure) at run time.

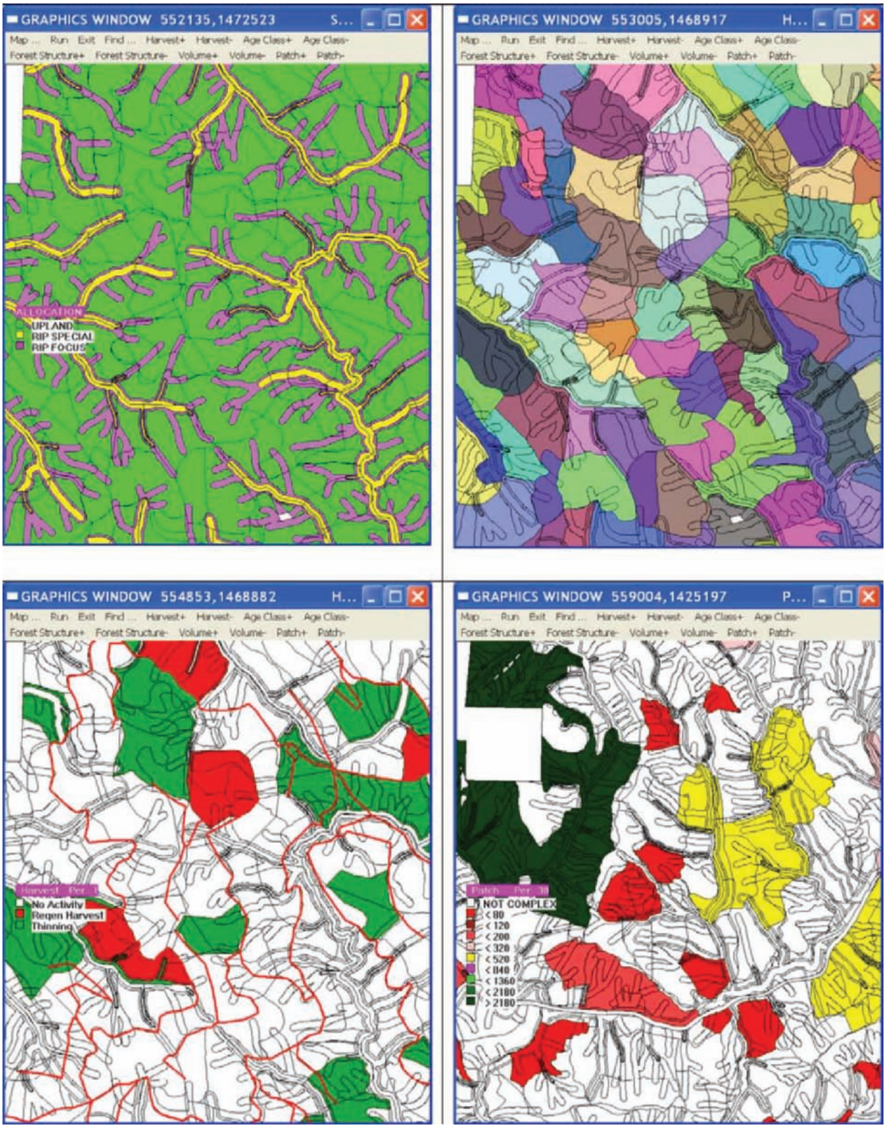

Figure 11-3. Upper Left: Land classification showing upland and two kinds of riparian zones. Upper Right: Harvest units averaging 20 ha. Lower Left: First 5-year partial cut (green) and regeneration harvests (red) and road system. Lower Right: Complex forest patches of different sizes containing habitat in layered and old forest structural components. (See also color plate 11-3 on p. CP10)

A transportation tree has been developed for all districts using the transportation planning software NETWORK 2000 (Sessions and Chung

2003). The transportation tree identifies the road network, existing and not yet constructed, that would be used to access each harvest unit.

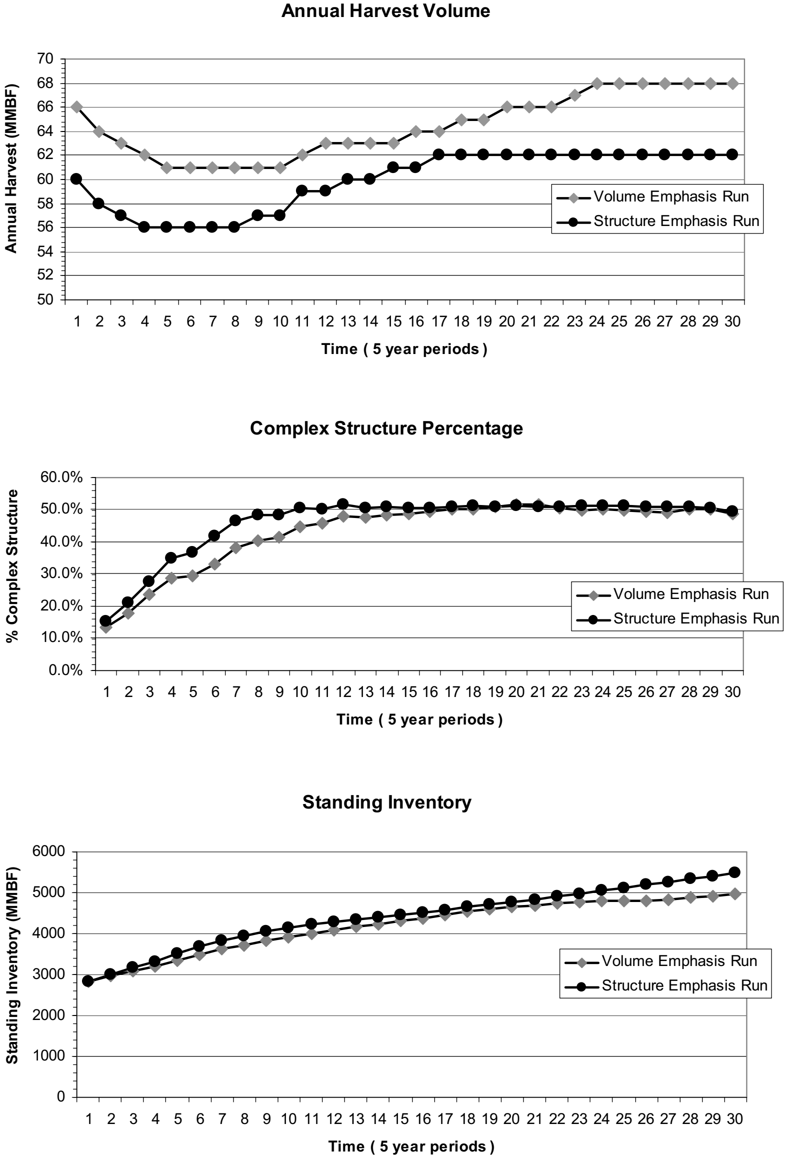

Figure 11-4. Harvest volume, complex forest structure, and standing inventory example for one district using two simulations; one emphasizing harvest volume and the other emphasizing achievement of complex structure in the shortest possible time.

Vegetation data from inventory collected on approximately 30% of the timber stands was created by stratifying stands into similar species, size and density and assigning average stand tables from the sampled stands to all stands in the strata. Each stratum was grown for 30 five-year steps with a variety of thinnings at various timing intervals and residual stand densities.

Geographic Information System (GIS) software, ArcInfo, was used to combine data layers to simulate ODF's land classification. Layers were used for the vegetation condition, physical characteristics, trust ownership, political boundaries, harvest units, habitat classifications, riparian boundaries, and road rights-of-way.

The assignment of prescriptions to parcels is done using the harvest scheduling model described in Section 5. By adjusting the relative values of the goals, different scenarios can be examined, for example trade-offs between timber outputs and time to achieve complex forest structure (Figure 11-4). By increasing the weight on the complex forest goal, the target of 50% complex forest is reached more quickly and the forest carries slightly more inventory, than when its weight is lower. Similarly, increasing the weight on the timber outputs delays the time to reach the target complex forest goals. If the weight on the timber outputs becomes relatively much greater than the objective function weights on complex forest, then the complex forest target may not be reached at all.

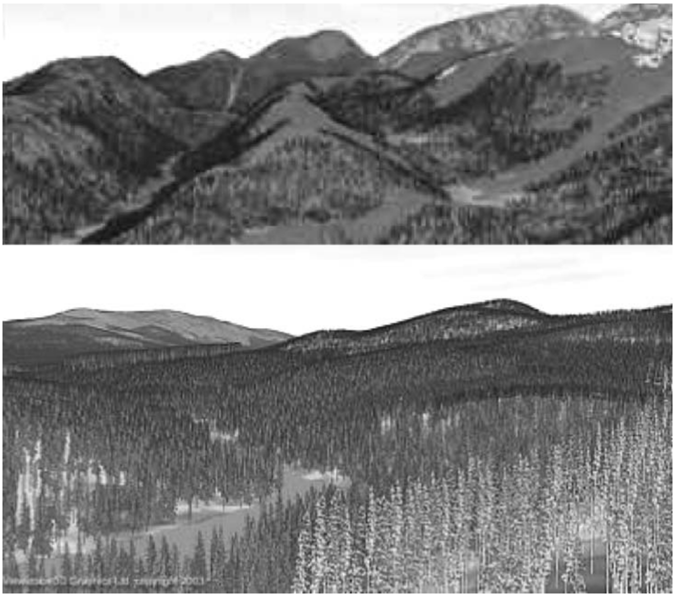

Figure 11-5. Graphical construction of flyover a managed landscape, courtesy of Viewscape-3D Graphics Ltd.

When the State models are complete, the agency will develop a three-dimensional flyover demonstration (Figure 11-5) on a sample portion of the landscape managed under the FMP and HCP (Alternative 1). The value of the flyover presentation, created using Viewscape3D Graphics Ltd software, will be to give the decision-makers and public a visualization of how the proposed plan will affect the landscape at selected times during the 150 year planning horizon.

8. MODEL VERIFICATION

To our knowledge, the State models are some of the largest, if not the largest, spatial forest models of their type. An important challenge is to understand if the model is functioning correctly. By this we mean, "Is the model following the rules and are the computations correct?" Just because a computer model runs, does not mean it is running correctly. There have been cases where well-known harvest scheduling models have run erroneously for several years without errors being discovered.

To help with debugging, ODF has developed two tools. The first tool is a GIS-based project which takes the solution and verifies that it satisfies all spatial rules for the first four time periods. The second tool is a Microsoft ACCESS database that takes the solution and independently verifies the harvest calculation for the 30-period planning horizon. The database also has the ability to answer questions regarding the accuracy of the spatial rules and to analyze the types of prescriptions and the acres and timing of the clearcut and thinning harvest types that were assigned to stands to solve the problem. After the solution passes these two tests, district teams, familiar with on-the-ground conditions, operational constraints and ODF's policy, guidance and direction, review the graphic and tabular output for operational feasibility. At both steps, data and logic errors are corrected and model rules are reviewed and changed to reflect strategic and operational accuracy. The Stand Visualization System (SVS) (McGaughey 1997) was used to project images of stand development over time to help management and stakeholders interpret existing and future stand conditions.

9. GOAL ACHIEVEMENT AND IMPLEMENTATION

The State models use optimization techniques to identify promising solutions to represent each alternative by adjusting goals and weights in the objective function. The Board must ultimately determine the level of outputs from the implementation of the FMP or direct the planners to develop additional alternatives. The alternatives will provide the Board with context for possible adjustments to the current FMP and to ODF for possible adjustments to their 10-year Implementation Plans that are used (via Annual Operation Plans) to implement Forest Management Plan strategies on-the-ground.

The State models will continue to develop as better data is available. With more stand level inventory and better methods of imputing characteristics to the unsampled stands the vegetation inputs will better reflect actual conditions. ODF will develop better software to improve the classification of stand structure, better ways to model silvicultural prescriptions to simulate stand management, and improve their GIS data. As data improves, it is anticipated that the linkage between strategic-tactical harvest schedule modeling and district operational plans will be strengthened for at least two reasons. First, substantial effort, time and cost are required to develop separate strategic plans (FMP), tactical plans (10-year Implementation Plans), and project-specific operational plans (Annual Operation Plans). Second, the roles of monitoring and adaptive management are recognized as increasingly important components of modern forest management. The ability to react in a more efficient way (faster and with lower costs) suggests reducing the number of planning levels. With better and more accessible data and technological advances in computer hardware and planning software, it may be feasible to analyze various management options or to integrate new information to help solve forest planning problems at the strategic, tactical and operational levels simultaneously.

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Chapter 12

LINKING MULTIPLE TOOLS: A CHINESE CASE

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Abstract: Forest and forest management in China have faced many problems during the past five decades. Human population growth, economic development, and resource insufficiency have made it difficult to pursue sustainable forest management in China. While China's forest policies have been improved, new technologies should be introduced into China's forestry system. There are many computer techniques that are useful for a variety of forest management activities. However, there are barriers for straightforward applications of computer technology in the current forest system in China. Both the technology and forestry system need adjustments. This chapter introduces convergent applications of geospatial techniques and forest modeling in data collection/management, forest harvesting, forest restoration, and forest protection in northeast China. A standard data management system eliminates the inconsistencies found in the traditional forest inventories; spatial considerations in harvest placement protect forested landscapes from further fragmentation; long-term forest simulations with a density-dependent matrix model optimize forest harvesting schemes; a forest classification system supports forest planning and protection; forest fire risk simulations allow forest managers to prevent and control forest fires in a spatially-explicit fashion; forest restoration models promote the best use of resources in silvicultural activities. All these computer applications share the same data sources and are sometimes dependent on each other. They are integrated into a decision-support system called FORESTAR®, which has been developed under the MapObject geographic information development environment. This integrated computer tool is applied in two forestry bureaus in northeast China.

Key words: Northeast China; forest inventory; forest modeling; decision support; forestry unit; forest management planning; ecosystem management; Baihe; Benxi.

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1. INTRODUCTION

China’s forest resources have undergone tremendous changes during the past five decades, and this has resulted in changes in the missions of forestry units across the country. In the state-owed forestry areas, forests had been naturally regenerated before forestry units were formed in the 1950s. These natural forest ecosystems were important timber sources and have been degraded by excessive forest harvesting during the past decades (Zhang et al. 2000); in the community-owed forestry areas, forests resources had been extensively damaged before forestry units were formed five decades ago. Continuous tree planting efforts helped increase forest plantation areas in the past five decades. As a result, forest cover across the country increased from 5.2% in 1950 to 16.5% in 1998 (Zhao and Shao 2002). However, the increase in forest cover did not ease nationwide timber shortages nor diminish ecological/environmental disasters. Protecting and restoring natural forests has become a major forestry strategy in China in the 21st century (Zhang et al. 2000).

China’s state-owned forestry enterprise was formed in the 1950s. Forest harvesting and regeneration activities were strictly administrated under forest operation regulations formulated by State Forestry Administration (SFA), formally known as China’s Ministry of Forestry. China is a large country and forest ecosystems vary across the country. The national forestry regulations were too general to provide site-specific guidance for forest management activities at a local level (Shao et al. 2001). For example, most natural forests in northeast China could not meet the national standard for natural regeneration after harvesting even though they were typical uneven-aged mixed forests. More specific forestry regulations formed in different times by different government organizations resulted in conflicts, controversies, and inefficiencies. For example, because forestry units could receive forest cultivation fund if they had “bare” land for plantations, valuable hardwood-species seedlings/saplings and young trees were cleaned off during harvesting. With the “supports” from the government, the cleaned sites were planted with 1-3 year-old pine and larch seedlings. Such a forest management practice was ecologically ineffective and economically inefficient because it not only altered the structure and composition of future forests but also increased the length of harvest rotations (Shao et al. 2001).

Although China’s new forest policy is encouraging, China’s forestry problems cannot be automatically resolved. The transition of China’s forestry needs both philosophical and technological changes. The fact is that there is no universal technique available for resolving all the accumulated issues associated with China’s forestry system. Instead, multiple techniques are needed and they must be integrated to support one another and maximize the efficiency of sustainable forest management.

Since 2001, we have been systematically studying the reforms of China's forestry in Jilin and Liaoning Provinces, northeast China. This chapter introduces key considerations in identifying individual techniques and explains how these techniques were incorporated into a decision support system, FORESTAR®, developed for promoting sustainable forest management in northeast China.

The case studies introduced in this chapter are from Baihe Forestry Bureau in Jilin Province and Benxi City Forestry Bureau in Liaoning Province (Figure 12-1). Baihe Forestry Bureau is located on the north-facing slope of Changbai Mountain and adjacent to Changbai Mountain Nature Reserve in the south (Shao et al. 1996). Benxi City is located in the southward extension of Changbai Mountain system. Both Baihe and Benxi are within Changbai Mountain Vegetation Zone, and are the center of temperate mixed forest ecosystems in the eastern Eurasian Continent (Barnes et al. 1989, Nakashizuka and Iida 1995). Baihe Forestry Bureau is state-owned forestry enterprise. Its geographical extent ranges from 127°53' to 128°34'E, and from 42°01' to 42°48'N. Forests in Baihe Forestry Bureau were composed of primarily old-growth hardwood, coniferous, and mixed forests before the 1970s. Extensive harvesting by either clearcutting (Shao and Zhao 1998) or selective cutting (Dai et al. 2003a) has degraded many forest stands (Zhou et al. 2006). Benxi City Forestry Bureau is a local forestry enterprise located at 123º34′-125º46′E and 40º49′-41º35′N. Forests in Benxi City area consist of secondary natural forests and plantations.

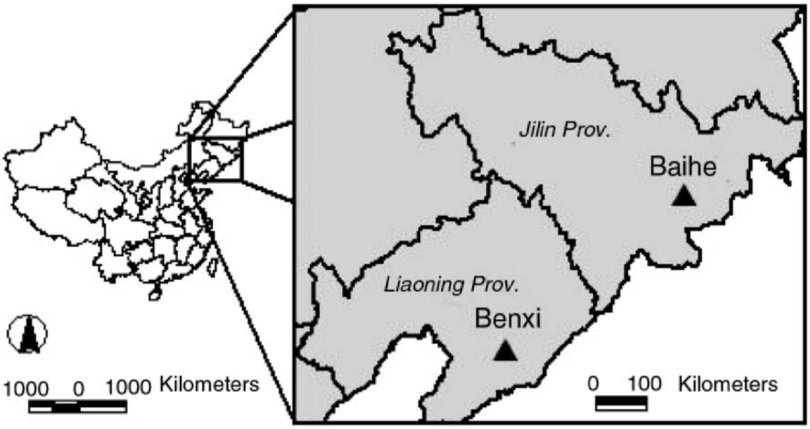

Figure 12-1. Locations of two study sites in northeast China.

2. FOREST MANAGEMENT IN CHINA

2.1 Forest management unit

China's state-owned forestry is the mainstream of China's forestry system, and is implemented under a clearly-defined, top-down hierarchical framework (Figure 12-1). Forestry units at each level have different responsibilities. The core of the framework is Forestry Bureau which is an independent accounting and planning unit. However, a forestry bureau does not have an authority to determine the quantity of timber harvesting. Such forest management activities at a forestry bureau are administrated and monitored by the upper-level forestry governmental units, including SFA and Provincial or Regional Forestry Bureaus. China's local forestry system is administrated by the local government but its forest management processes must follow the forestry regulations from SFA.

The forestry unit under Forestry Bureau is Forest Farm. An average forest farm consists of tens of thousands of ha of forestland. Workers and their families reside inside a forest farm where they are employed. A forest farm is a management execution unit for forest management under the administration of a forestry bureau.

The Compartment is a planning unit used to organize forest management on forest farms. Compartment-level activities include data summarization, mapping, and forest management planning (Yu 1993). The boundaries of compartments, normally the divisions of natural topographic features, are drawn from topographic maps and aerial photographs, and marked *permanently* on the ground. Covering hundreds of ha, each compartment within a forest farm has a unique ID number that does not change over time.

The Sub-Compartment is the preliminary unit or parcel for forest inventory and management implementation. Each sub-compartment is supposed to be unique and thus different from its surrounding sub-compartments in at least one of the following factors: forest use type, dominant tree species, stand age, density, site index, soils, forest origin, slope, aspect, etc.. The average area of sub-compartments is about 15 ha in northeast China and less than 10 ha in the south (Yu 1993). Depending on which forest inventory is used, there are two parallel sets of sub-compartments within each compartment (details are explained in the next section).

The top-down forestry administration system relies on bottom-up information aggregation. The fundamental forestry unit is sub-compartment and any information errors at sub-compartment can be propagated during the information aggregation process. The existing forest management planning is conducted at the compartment level. Shao et al. (2005) compared the sub-compartment-based and compartment-based harvesting schemes. The former resulted in clustered harvesting patterns and the latter resulted in scattered harvesting patterns. Dai et al. (2006) compared traditional, compartment-oriented classifications of forest zones with GIS-based, sub-compartment-oriented classifications of forest zones. The former used the average forest conditions within compartments and could wrongly presented spatial patterns for ecologically sensitive forests.

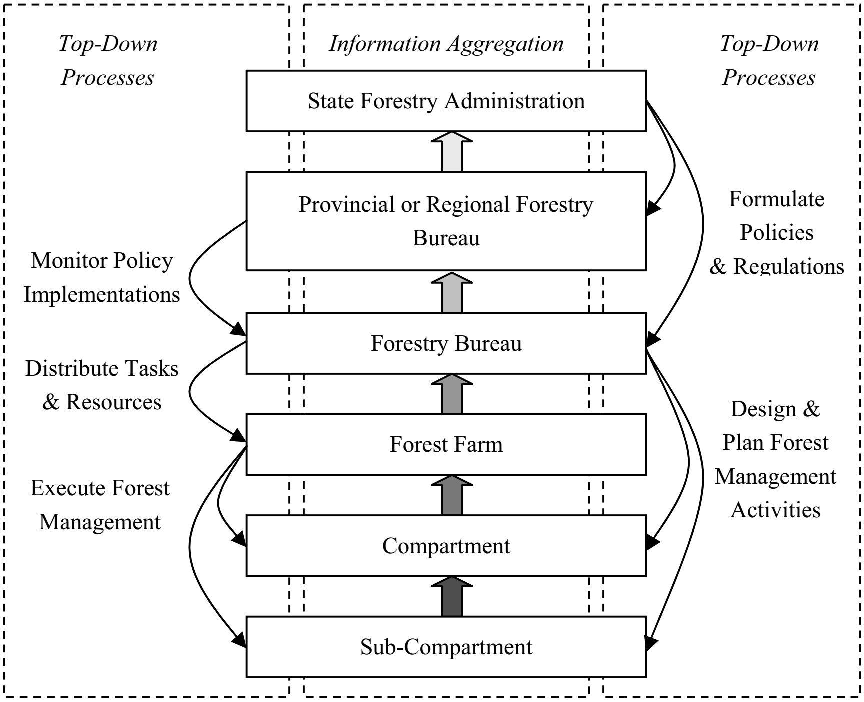

Figure 12-2. A hierarchical structure of the state-owned forestry system in China. The line arrows represent the top-down processes and block arrows show information aggregation: the darker an arrow, the more originality.

2.2 Forest inventory systems and data management

China's forest resource inventory system is implemented at three levels (Tang et al. 2006).

While the 1st-Level Forest Inventory (1st FI) is used to monitor forest resources at National or Regional level, the 2nd- and 3rd-Level Forest Inventories, or 2nd FI and 3rd FI, provide data useful for forest management activities.

The 2nd FI takes place approximately every ten years with systematic sampling schemes in every sub-compartment within a forestry bureau. It produces stand data and forest parcel maps that are used within a forestry bureau for forest management planning over the subsequent 10-year period. The boundaries of sub-compartments are determined with topographic maps and aerial photographs and are transferred to forest parcel maps. Only compartment boundaries are marked on the ground. The 2nd FI is implemented by provincial or regional forest inventory organizations.

The 3rd FI is conducted every year by individual forestry bureaus. These data are used for designing yearly forest management activities within selected sub-compartments. The selection of management targets (compartments) is based on the 2nd FI. Each selected compartment is divided into sub-compartments on the ground before forest management takes place.

The sub-compartments defined with the 2nd FI are called the 2nd-level sub-compartments (2nd SC) whereas those defined with the 3rd FI are called the 3rd-level sub-compartments (3rd SC). The 2nd FI and 3rd FI are inconsistent in many ways (Table 11-1). Both the 2nd SC and 3rd SC boundaries are re-defined when a new inventory takes place. The inconsistencies and dynamics in sub-compartments' shapes, sizes and locations reflect some fundamental problems in forest management in China's forestry system. Due to these problems, it extremely difficult, if not impossible, to update the long-term forest data with the annual measurements provided by the 3rd FI. This is problematic because sustainable forest management using computer-aided, automated decision-support systems requires current forest inventory information aggregated across several spatial scales.

Table 12-1. Major differences between the 2nd-FI and 3rd-FI.

	The 2nd-Level Forest Inventory	The 3rd-Level Forest Inventory
How	Sub-compartments are drawn on paper by referring to aerial photography, topographic maps and old inventory data	Sub-compartments are measured with compasses and measuring tapes on the ground
When	Every ten years	Every year
Where	Entire Forestry Bureau	Selected Compartments
What for	Planning forest management and providing info for the 3rd-FI	Designing forest management activities
What is	Measuring trees at systematic sample points	Measuring every tree within a sub-compartment

2.3 Forest management planning

Forest management planning at each forestry bureau each year must consider at least the following three factors:

(1) Satisfying the requirements from the top forestry organizations. Between the 1950s and 1980s, the government encouraged forest harvesting by setting up the minimum harvesting budget. In the past two decades, the government restricted forest harvesting by setting up the maximum harvesting budget. Because of the changes in the requirements from the government, forest management planning had to adapt to philosophical changes.

(2) Meeting the short-term needs of a forestry bureau. Human population increased five fold in forestry areas in China in the past five decades (Zhang et al. 2000). Typically there are too few forest resources to support the increased population living within a forestry bureau. Thus, from a social perspective, harvesting whatever timbers they have is usually only realistic choice for a forestry bureau.

(3) Utilizing governmental supports. The central government provides a variety of funds to forestry organizations each year. One is the traditional forest cultivation fund that must be used for forest restorations. Another is the ecological service fund which was initiated in 2004. The government distributes ecological subsidies proportional to the area of Key Ecological Forest (see section 4). Because of the lack of reliable information, many funds were either replicated or omitted at the local level.

Forest management planning is determined by governmental requirements/supports, local's needs, and forest conditions. On one hand, local forestry units want to get funding and other supports when they provide bottom-up information feedback. On the other hand, the higher levels of government want to control everything at local levels by enforcing top-down policies (Dai et al. 2006). Frequent and inevitable contradictions between the upper and lower levels of forestry administration have caused mistrust within the hierarchy of forestry units. For example, iron fences had to be installed on the ground to convince SFA that the natural forest protection policy was well implemented at the local level (Zhao and Shao 2002).

China's timber demands are increasing in step with China's rapidly growing economy. However, China's timber resources are becoming less available (Zhao and Shao 2002). Managing the existing forest resources with ecologically and economically sound methods is critically important. More consistent and efficient methods to collect, manage, and utilize forest information essential for addressing China's forest management issues.

3. IDENTIFYING COMPUTER TECHNIQUES

To help resolve the forest management issues in China, accurate information acquisition and management, timely information feedback from the bottom to top, multi-purpose forest management activities, and long-term forestry considerations have to be improved. Computer technologies can play an important role in the transition of China's forestry.

3.1 Digitally determining compatible forest units

Neither of the 2nd and 3rd SC is without problems. Developing a single sub-compartment system to replace the 2nd SC and 3rd SC will solve the inconsistency between the 2nd and 3rd forest inventories. Should one of the two sub-compartment systems be the only choice, the 3rd SC is preferable because the 3rd SC are used to implement forest management activities. However, the boundaries of 3rd SC are determined directly on the ground, and continuous slope and aspect gradients are hard to identify in the field. For example, the natural forest protection policy restricts harvesting forests growing on slopes ≥25° and such a boundary line cannot be readily located on the ground. Tang et al. (2006) developed an alternative technique that intersects ecological land types (ELT) determined with digital elevation models (DEM) (Shao et al. 2004, Dai et al. 2003b) with the 2nd-SC determined with high-resolution satellite data.

The new technique was demonstrated at Jianchang Forestry Farm, Benxi City, Liaoning Province of China. The ELT data layer was generated using a 10-m DEM derived from 1:10,000 topographic maps. Slopes were classified into three categories: flat land (<5°), gentle slope (5-25°) and steep (≥25°). Aspects were classified into two categories: mesic aspect with azimuth ranging from 0° to 135° and from 315° to 360° and dry aspect between 135° and 315° in azimuth. Overlaying the slope and aspect data layers resulted in 5 ELT: Bottomland, Dry-Gentle Slope, Mesic-Gentle Slope, Dry-Steep Slope, and Mesic-Steep Slope. These spatial analyses can be performed using standard functions of geographic information systems (GIS), such as ArcGIS (www.esri.com) (Shao et al. 2004).

Forest Inventory and Planning Institute in Liaoning Province delineated forest vegetation types by visually interpreting natural color 2.5-m SPOT-5 satellite data (www.spot.com). The vegetation classification system consisted of eight forest types: pine (*Pinus koraiensis*) plantation, larch (*Larix japonica*) plantation, walnut-ash (*Juglans mandshurica* - *Fraxinus mandshurica*) forest, birch (*Betula costata*) forest, maple forest, oak (*Quercus mongolica*) forest, mixed hardwood forest, and mixed hardwood-pine forest.

Table 12-2. ELT-vegetation combinations for Jianchang Forestry Farm, Benxi City, Liaoning Province.

ELT Type	Vegetation Type
Bottomland	Pine Plantation
	Larch Plantation
	Mixed Hardwood Forest
	Walnut-Ash Forest
Dry-Gentle Slope	Pine Plantation
	Birch Forest
	Larch Plantation
	Maple Forest
	Mixed Hardwood Forest
	Oak Forest
	Mixed Hardwood-Pine Forest
	Walnut-Ash Forest
Mesic-Gentle Slope	Pine Plantation
	Birch Forest
	Larch Plantation
	Maple Forest
	Mixed Hardwood Forest
	Mixed Hardwood-Pine Forest
	Walnut-Ash Forest
Dry-Steep Slope	Pine Plantation
	Birch Forest
	Larch Plantation
	Maple Forest
	Mixed Hardwood Forest
	Oak Forest
	Walnut-Ash Forest
Mesic-Steep Slope	Pine Plantation
	Birch Forest
	Maple Forest
	Mixed Hardwood Forest
	Oak Forest
	Mixed Hardwood-Pine Forest

By overlaying the ELT data layer with vegetation data layer, a new sub-compartment system was developed. After a filtering process, the remaining polygons all had areas ≥1 ha, which was the minimum management area. The resultant sub-compartment system contained 32 ELT-vegetation type combinations (Table 12-2). The technological advantage of the new sub-compartment system is that it meets the requirements of the 2nd and 3rd forest inventories and facilitates computer-aided data and information management. It is called compatible sub-compartment system (CSS).

Field applications of CSS suggested that the digital technologies can be more efficient than the conventional methods. For example, the 3rd-FI normally requires 15 people to measure over one thousand sub-compartments each year, but CSS requires only seven people to carry out the job. The annual reduction of labor cost is more than the one-time investment required to obtain the GPS technology needed for field implementation of CSS.

The 2nd-FI under the conventional system requires three people per a crew whereas CSS needs only two people per crew. The conventional system requires crews following straight-line transects in the woods to locate plots. This process is relatively slow and difficult when understory vegetation is dense. When GPS navigation is used with CSS, the crews can readily move around difficult territories by using off-set points. This makes field work easier and faster. Some forest inventory organizations have started to use GPS based data loggers. This makes CSS processes even more efficient and makes CSS data more manageable.

Because every sub-compartment is associated with a combination of ELT and vegetation types, forest management at each sub-compartment can be carried out in a systematic manner. For example, forest protection and restoration are the most important management activity on the steep slopes and only low-intensity harvesting should be used; forests growing on gentle slopes are managed for timber and relatively high-intensity harvesting can be used; forests growing on bottomland cannot be cleared because many of them serve as filters for water/soil protection. Therefore, forests with the same structure and composition are managed differently if they belong to different ELT; management of forests within the same ELT can be tailored to their structure and composition. For example, forest restoration processes on the steep slopes vary with forest structure and compositions that represent different succession stages of the primary forest.

3.2 Forest modeling for optimizing forest harvesting

The broadleaved Korean pine mixed forest is a dominant native ecosystem in eastern mountainous areas in northeast China (Dai et al. 2005). Efforts have been made to develop individual-tree-based forest models to simulate forest dynamics under various climate and management conditions (e.g., Shao et al. 1994). However, these models cannot be easily linked with China's production forestry inventories because they provide diameter distribution data rather than individual tree data. Matrix models use diameter distribution data as input (Buongiorno 2001) and supposedly can be linked with available forest inventory data in China. Shao et al. (1995) developed a matrix model with constant transition probabilities. However, matrix models based constant diameter transition probabilities may not provide realistic projections for forests with timber harvesting because they cannot account for the tree growth response associated with thinning. Shao et al. (2005) modified the existing model based on field observations in a forest stand and developed a model with transitional probabilities that are related to relative diameter classes. To assure valid projections for forests under a broad range of harvest and environmental conditions, the transition probabilities were determined with data from a variety of forest stands.

Shao et al. (2006) developed a matrix model with data collected from 40 sample plots, sized between 0.2 and 1 ha, in the broadleaved-Korean pine mixed forests of the Baihe Forestry Bureau and Changbai Mountain Nature Reserve. There were two measurements on each plot made at intervals from 7 to 10 years. The observed diameter growth rate was normalized into 5-year-period periodic growth. All the trees measured were grouped into 4 cm-interval diameter classes. The data from 36 plots with varied sizes were used to estimate parameters of the matrix model and the remaining four 1ha plots were used to test the model. The four validation plots represent four typical stands, including basswood-Korean pine forest, oak-Korean pine forest, birch-Korean pine forest, and hardwood forests.

By using the stepwise regression technique, a matrix model composed of an up-growth equation, a mortality equation, and an in-growth equation was parameterized as follows:

$$b_{i,t} = 0.007 - 0.021\ln(G_{i,t}) + 0.92265D_{i,t} - 1.02368D_{i,t}^2 \tag{1}$$

$$m_{i,t} = 0.0294 + 0.01089G_{i,t} - 0.2426D_{i,t} + 0.28111D_{i,t}^2 \tag{2}$$

$$I_t = 3 + 0.032N_t - 0.185G_t \tag{3}$$

where, $b_{i,t}$ is a probability that a tree of diameter class i moves to a larger diameter class $i + 1$ from time t to $t + 1$, $m_{i,t}$ is a probability that a tree of diameter class i dies between time t and $t + 1$, I_t is the in-growth rate to the smallest diameter class from natural regeneration, $G_{i,t}$ is basal area (m^2/ha) for trees in the ith diameter class at time t, $D_{i,t}$ is midpoint diameter (cm) in the ith diameter class, N_t is stand density (trees/ha) at time t, and G_t is stand basal area (m^2/ha) at time t.

The model was validated by comparing diameter distributions between model simulations and ground measurements (Shao et al. 2006). Simulations suggest that dynamic processes of immature stands can reach to equilibrium within decades if no disturbance occurs (Figure 12-3). This explains the effectiveness of density control in the model. The density control also makes the model capable of increasing growth rates in response to simulated selection harvests (Figure 12-3). In this particular example, the total harvest exceeds the initial stand stocking within seven harvests or 245 years. Such selective cutting can help obtain 20% more timber than conventional clear-cutting with a harvest rotation of at least 300 years. This matrix model simulation agrees well with gap model simulations by Shao et al. (1994). All these positive features of the density-dependent matrix model support its applications in comparing different harvesting schemes with a range of cutting intensity and rotations.

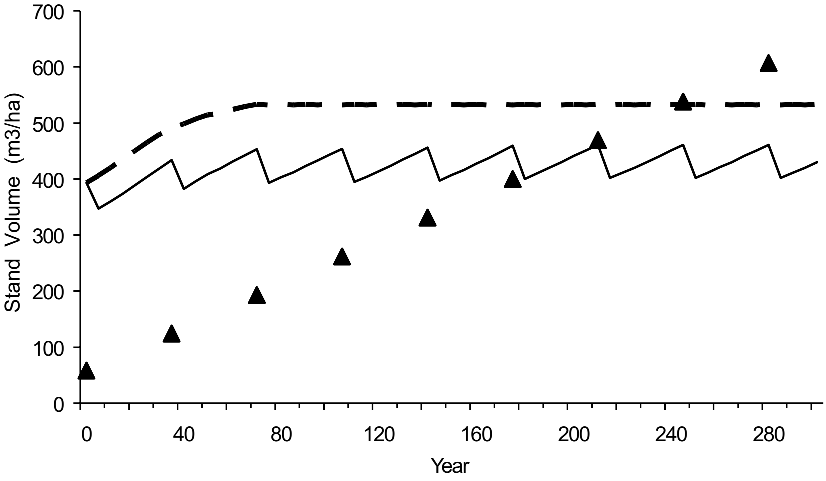

Figure 12-3. A comparison of forest dynamics between un-harvested (dashed line) and harvested forest stands (solid line). Dots (triangles) indicate accumulated forest harvests.

An optimal harvesting scheme for a forest stand within a period of time is based on three constrains: (1) forest harvesting cannot exceed growth; (2) total timber production should be relatively high; (3) forest size diversity cannot decline. Shao et al. (2006) compared 35 harvesting schemes, which resulted from seven different harvesting rotations (10, 15, 20, 25, 30, 35, and 40 years) and five harvesting intensities (10, 15, 20, 25, and 30%). Over 300 years of simulation time, the total net growth ranged from 150 to 600 m^3/ha while the total harvest ranged from 330 to 690 m^3/ha. There were 12 harvesting schemes that had positive net growth. Among them, the 25-year at 15% and 35-year at 20% harvesting schemes had relatively high harvest levels (nearly 600 m^3/ha). Both harvesting schemes increased tree size diversity but the 25-year at 15% harvesting scheme was most effective in enhancing size diversity.

In fact the criteria of optimal harvest schemes can be modified when new requirements need to be incorporated into harvest optimization. The simulation experiment and optimization analysis can be accomplished with a user-friendly interface (Figure 12-4), which has been developed through modifications of the simple harvest scheme interface (Shao et al. 2004).

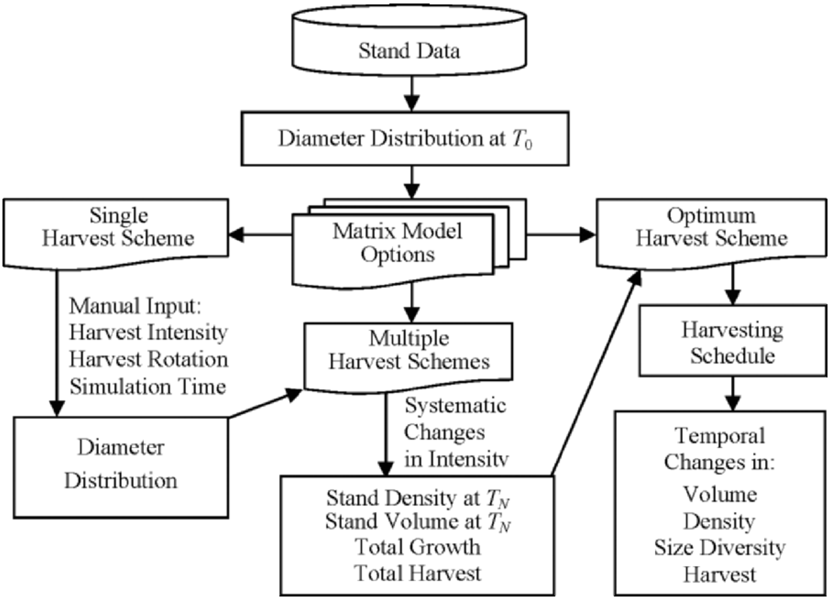

Figure 12-4. An illustration of matrix model interface for harvest optimization applications.

Selection of specific sub-compartments for harvesting is determined using spatial analysis at a landscape (forest farm) level. Automated data input for running the matrix model at any selected sub-compartment is realized by linking of the matrix model with stand inventory data within a sub-compartment.

The matrix model interface has three options:

(1) Single Harvest Scheme. The matrix model is run with user defined harvest parameters, such as harvest intensity (% of volume removed from a stand), harvest rotation (years), and simulation time (years). By examining changes in diameter distribution (size diversity) over time, forest managers

can better understand the characteristics of the stand simulated. This structural information is helpful for determining the range of harvest intensities for multiple harvest schemes.

(2) Multiple Harvest Schemes. Under a given harvest intensity, the model simulates forest dynamics with different harvest rotations. If the total forest growth is greater than total harvest at the end of the simulation time, the harvest scheme is a candidate in further comparisons. After numerous simulations within the range of harvest intensities, the candidate harvest schemes are compared and the harvest scheme with the highest harvest volume is considered optimum.

(3) Optimum Harvest Scheme. The model runs a simulation with the optimum harvest parameters and lists a harvest schedule indicating what harvesting method is used over the total simulation period. The final simulation also provides detailed dynamics in density, volume, and size diversity of a forest stand.

The flexibility of the digital optimization procedure allows the involvement of forest managers in making decisions for sustainable management of the real-world forests. This is particularly useful when computer simulations produce similar optimum harvesting schemes. Under such a circumstance, forest managers can be assisted with model simulations but do not have to solely rely on model simulations. This incorporates active involvement of human intelligence and perception in computer-aided decision-making processes.

3.3 Forest fire management

Forest fires occur every year in northeast China. Tremendous efforts have been made to prevent and suppress forest fires. Sound forecasts of forest fires are critically important for effective use of financial and labor resources in forest fire prevention. Quantifying forest fire risks in spatially-explicit fashion is a common approach for forest fire forecast (Chuvieco and Salas 1996, Johnson and Gutsell 1994). However, such an approach was infeasible in China until recently when geospatial data became available (Hu 2003).

Xu et al. (2006) examined forest fire risks for Baihe Forestry Bureau in relation to three factors: fuel, topography, and anthropogenic activities. The fuel factor includes 4 variables: tree species, canopy density, stand age, and average diameter. The topographic factor includes 3 variables: slope, aspect, and altitude. The anthropogenic factor includes 4 variables: population density, road density, distance to roads or residential areas, and distance to farmlands. The geospatial data used for analysis included Landsat Thematic Mapper (TM) data acquired in 1987 and Enhanced Landsat Thematic Mapper (ETM+) data acquired in 2000, forestry inventory databases in 1987 and 2000, and 25m-resolution digital elevation models (DEM). The 1987 data set was used to develop a fire risk model and the 2000 data set was used to forecast fire risks. Fire observation data between 1987 and 2000 were used to validate the model.

Both principal component analysis and regression analysis suggested that fire ignition rate is not sensitive to the fuel factor but is sensitive to topographic and anthropogenic factors. Fire ignition rate increased with elevation and proximity to human. The elevation control on fire ignition resulted from changes in temperature and precipitation along elevations whereas the human control on fire ignition explains that most forest fires are started by human activities. Because most local residents lived at lower elevations, the fire ignition rate at lower elevations (below 900m) was significantly higher than that in higher elevations. For sub-compartments at higher elevations (above 900m), the topographic factor was the most important for predicting fire ignition. Such understanding about forest fire ignition is helpful in managing wildfire risks. Namely, more efforts should be made in educating the local people in order to reduce the number of ignitions.

Fire risk mapping illustrates fire risk in a spatially-explicit fashion. Every spring, forest-fire-prevention check points are set up throughout the forested areas. The fire risk map has helped the Baihe Forestry Bureau relocate some forest-fire-prevention check points to areas of greater risk.

4. AN INTEGRATED COMPUTER INTERFACE

Sustainable forest management is a comprehensive process, in which multiple computer techniques are essential. The computer applications discussed above are three specific examples. There are other computer applications that are also important in China's forestry. The integrated use of multiple computer applications can increase efficiency and consistency of forest-management decision making. Such an integration has be partially realized with a decision-support system, known as FORESTAR® developed under Map Object geographic information support environment (www.esri.com) for promoting sustainable forest management in northeast China (Shao et al. 2005). FORESTAR® consists of three modules and each module consists of task-driven interfaces (Figure 12-5). The standard forest inventory system provides stand and spatial data for running all the modules and interface components. The three modules are closely related because some of their components or interfaces share data and results across the modules.

4.1 Forest harvest module (FHM)

A two-step decision-making process is built in FHM (Shao et al. 2005). The first step is for selecting harvest target (sub-compartment) within a landscape and the second step is for simulating harvest at a stand level (sub-compartment). Two interfaces were designed corresponding to the two steps. The Target Selection Interface allows comparing and optimizing landscape structure for selecting different forest targets for harvesting. After excluding protected forests, harvest targets are selected by referring to operation costs (clustered harvesting is less costly than scattered harvesting), timber yield (harvesting stands with the most volume), landscape integrity (avoiding further fragmentations of forest patches), and non-wood products (protecting forests that produce other valuable goods and services). Once a forest stand is selected for harvesting, the matrix model interface is used to optimize harvesting schemes.

The two-step decision-making process meets the needs of sustainable forest management at two spatial scales. At the landscape scale, the harvesting targets are selected and located on the basis of spatial considerations; at the stand scale, cutting intensity and rotation are determined on the basis of temporal considerations. Such a computer application results in a spatially- and temporally-explicit plan for forest harvesting. Such a decision-making process facilitates sustainable forest management.

4.2 Forest protection module (FPM)

The FPM contains three interfaces: forest classification, forest health, and forest fire risk simulation. The purpose of FPM is to identify forests that need to be protected, forecast pests and diseases, and provide forest managers with information on fire risk.

China started to employ a new forest classification system throughout the country in 2004 (State Council of China 2003). All forests in China are grouped into three classes: Key Ecological Forest (KEF), General Ecological Forest (GEF), and Wood-Commodity Forest (WCF). KEF is protected from logging, GEF can be logged with low-intensity selective cutting, and WCF is managed for wood products. SFA formulated nationwide criteria of forest classification and forest classification maps are made at the forestry-bureau level under the monitoring of provincial forestry bureaus. At least one-third of forestland was classified as KEF in most provinces. The central government provides ecological subsidies to forestry organizations with KEF. The Forest Classification Interface can help determine where different forests are located within a forestry bureau. This is an essential step prior to the determination of any forest management activities.

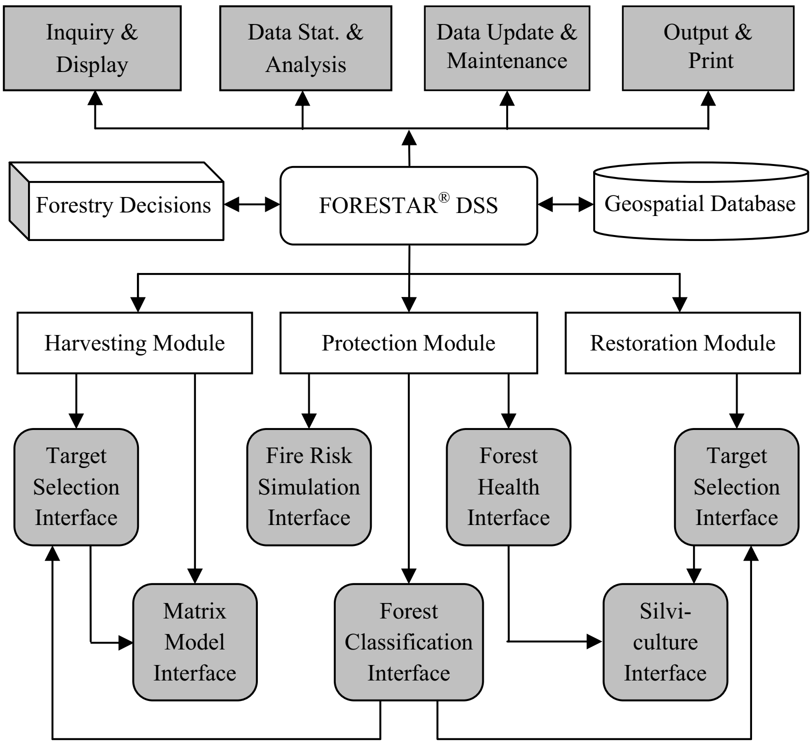

Figure 12-5. Major interface *components* of FORESTAR® Decision-Support System.

Forest pests and disease cause tremendous damage to Chinese forests every year (Zhang et al. 2000). The Forest Health Interface has two functions: field observation data entry and forest cleaning guidance. The former helps monitor forest health and latter is helpful for specifying health-treatment silvicultural activities.

The Fire Risk Simulation Interface includes fire risk mapping (as discussed above) and fire spread prediction. The fire risk mapping is useful for preventing forest fires whereas fire spread prediction is useful for timely suppression of wildfires. Wang (1992)'s fire spread model was incorporated into the Fire Risk Simulation Interface. The potential rate of fire spread is estimated based on daily highest air temperature, mean wind speed at noon, and daily lowest air humidity. It is then adjusted with information about fuel biomass, wind direction, and topographic conditions.

4.3 Forest restoration module (FRM)

Forest restoration in forested areas of northeast China includes three major activities: (1) cleaning shrubs and herbs within five years after seedlings were planted at harvesting sites; (2) thinning secondary forests; and (3) tending low-productivity forests. The central government provides a large amount of funding every year to support forest restoration activities. It is essential to make the best use of funds at the local level.

Based on forest classifications and stand information, each sub-compartment is assigned a type of restoration activities, including regeneration, cleaning, thinning, and tending. Each type of silviculture is divided into three urgency levels: the most urgent, urgent, and less urgent. A new attribute item representing the type and level of cilvicultural activities is added into the geospatial database. A table of costs corresponding to different silvicultural activities is also linked with the geospatial database.

The Target Selection Interface is used to select the targets of silvicultural activities based the availability of funds. It can also be used to determine the range of funds needed for necessary silvicultural activities. The former assures the best use of governmental funds whereas the latter helps foresters plan and apply for funds from the government.

5. THE FUTURE

Although computers are used in almost every department or division under each forestry bureau, forest data are currently available only to the forest management planners. The user-friendly graphic interface of FORESTAR® simplifies the use of forest inventory data and encourages data access by forestry professionals at all levels of the agency. This enhances the transparency of information flow among hierarchical forestry units. When the same database is freely accessed, bottom-up information aggregation and top-down administration processes (Figure 12-2) can be improved. Such information flow will facilitate applications of adaptive forest management.

The Internet infrastructure is under construction in China's forestry organizations, and some parts are already completed. When the internet-based data management system is formally implemented, information flows between hierarchical forestry units will be more transparent. Forest management planning will become more consistent and systematic among all the levels of forestry organizations. More computer tools will be needed and they will play a more important role in sustainable forest management. Of course, computer tools need continuous improvement by using current data, new knowledge about forest management, and advances in computation technology.

ACKNOWLEDGMENTS

The case studies used in this chapter and the FORESTAR® were financially supported by the Hundred-Expert Program from Chinese Academy of Sciences and Agriculture Enhancement Program from China's Ministry of Science and Technology. The authors are thankful for every effort made by graduate students, namely Ruili Lang, Fei Wang, Hui Wang, Lina Tang, Wenchun Wu, Baoying Xiao, Dong Xu, and Li Zhou. FORESTAR® was programmed by Yingshan Li. Forestry officials from both Baihe Forestry Bureau and Benxi City provided invaluable assistance.

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PART IV

CONCLUSIONS

Chapter 13

FROM DATA TO SUSTAINABLE FORESTS[*]

Towards digital forestry

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Abstract: We begin by introducing a simple process model that represents the classic process of getting from data about the forest to management actions. An analogous process in the context of sustainable forest management would be vastly more complicated, so object-oriented analysis and design provides a better starting point for thinking about designing a system of interoperable systems needed to support sustainable forestry. The evolution of such systems will be facilitated by a new breed of forester whom we call the digital forester: students well versed in the collaborative application of today's simpler systems.

Key words: Digital forestry; data acquisition; data analysis; information integration; forest sustainability; interoperability.

1. THE ESSENCE OF THE MODEL

Forestry, as a science-based management discipline, has existed for well over 100 years. Emphasizing its basis in science, we might visualize the classic forestry enterprise of timber management circa 1955 as a process model (Figure 13-1), in which data are acquired from the forest environment, analyzed, and the resulting information then interpreted, synthesized, and ultimately applied to the business of growing timber. The development and application of yield tables provide a simple case in point, and this simple model (Figure 13-1) is a reasonably accurate representation.

The modern equivalent for the forestry enterprise, concerned as it is with sustainable forest management, superficially does not look much different (Figure 13-2), although the differences are profound. Whereas 50 years ago,

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G. Shao and K. M. Reynolds (eds.), Computer Applications in Sustainable Forest Management: Including Perspectives on Collaboration and Integration, 261–267.

a typical question driving management might be concerned with maximizing return on investment over the life of a stand rotation, the question now is more likely to be concerned with whether or not the forest ecosystems within a region are being managed sustainably.

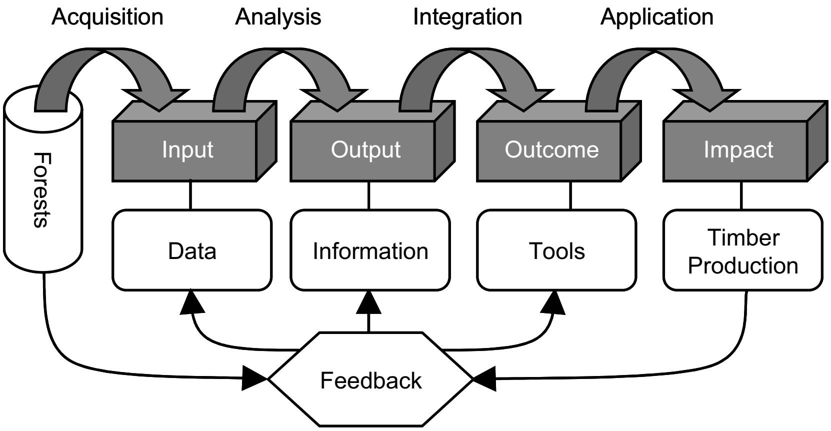

Figure 13-1. Forestry as a science-based process circa 1955.

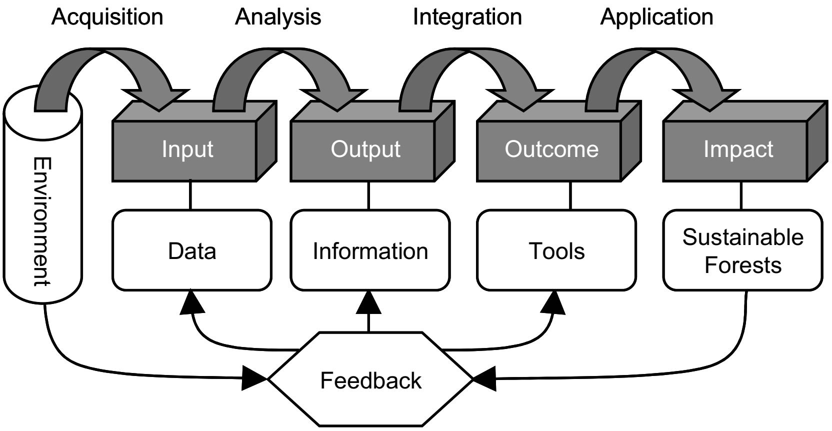

Figure 13-2. The modern equivalent of forestry as a science-based process, in which the focus has changed to the sustainable management of forest ecosystems.

Notice (Figure 13-2) that we have simply changed "Timber production" to "Sustainable forests," and changed "Forests" to "Environment," compared to Figure 13-1. These two changes are profound, first because the spatial scale of the respective questions is drastically different, and because the associated data requirements have increased from a few simple stand and economic metrics to scores, if not hundreds, of variables. Secondly, there are not only many more biophysical variables to consider when attempting to evaluate the state of forest ecosystems, but, in the context of sustainability, now we also need to consider the social and economic dimensions of "environment."

Our modern model (Figure 13-2) no longer accurately portrays the *process* of forest management in the context of managing for sustainable forests, given all the new complexity associated with hundreds of variables, dozens of perhaps interrelated analyses, multiple support systems, and so on. The model has become a more conceptual and highly stylized representation of a very complex process. We can, however, improve upon the utility of the model for purposes of subsequent discussion with a simple change of perspective. Rather than a flow diagram for a perhaps hopelessly complex process model, think of the model instead as a first approximation to a *class diagram* in the sense of object-oriented analysis and design (Booch 1994). Now, data, information, and tools become classes to be instantiated by appropriate collections of objects, and acquisition, analysis, and integration become the respective class methods.

So what, in the end, is the essence of this model? We have prefaced this volume by briefly introducing the concept of digital forestry. We return to the concept here, because it was a primary motivation for this volume, and because it is, in fact, the essence of our model (Figure 13-2).

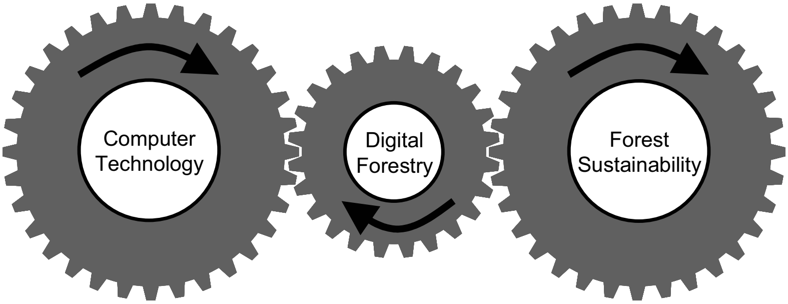

Figure 13-3. Innovations in computing and analytical requirements to support sustainable forestry drive the implementation of digital forestry.

2. DRIVERS OF DIGITAL FORESTRY

Computer-based technologies to support sustainable forestry have been the central topic of this volume. One way to visualize the relations among these technologies, digital forestry, and forest sustainability is as a gear train with three gears (Figure 13-3), in which both computer technology and forest sustainability are represented as drive gears. Thus, in this model, application of computer technology in contemporary forest management is driven by the needs of sustainable forestry, and conversely forest sustainability is promoted by computer technology. Note, however, that digital forestry functions as an "idler" gear within the gear train that keeps both drive gears rotating in the same direction.

3. PUTTING THE "DIGITAL" INTO FORESTRY

Chapters 2 through 12 of this volume have reviewed a variety of digital techniques and technologies, each of which is applicable to one or more of the four activities (Figure 13-2) of acquisition, analysis, integration, or application needed to support the objectives of sustainable forestry.

This volume begins with a look at important recent developments in the acquisition of spatial data because such capabilities are so fundamental to a science-based analytical approach to sustainable forest management. In particular, chapters 2 and 3 present new remote sensing techniques for acquiring forest data that could not be obtained with earlier techniques. Although these techniques are highly sophisticated, they are being delivered as computer-based systems that should be relatively easy to apply by geospatial technical staff of forest management organizations. The related technology of global positioning systems (GPS) has only been alluded to somewhat incidentally, but GPS likewise represent an important technological advance in terms of facilitating acquisition of site-specific information for management of forest resources.

Contemporary capabilities to rapidly and repeatedly acquire vast amounts of spatial data about numerous forest attributes are, however, something of a double-edged sword. The utility of all this information heavily depends upon its being well organized and easy to access. Thus, information management (Chapter 4) has an extremely important role to play at the interface between acquisition and analysis (Figure 13-2). The magnitude of the challenge to information management can perhaps best be appreciated from the perspective that the representation of information we seek amounts, in a very literal sense, to a digital forest.

The basic activities of data analysis are to extract information from data, and, typically, to formalize the information in the form of a mathematical model or models. Modern statistical tools are such an integral part of the scientific process that supports sustainable forest management that we felt it unnecessary to address this vast topic within the scope of this text. However, for the sake of completeness, let it suffice to say that the products of such analyses are typically manifested in applications for road and harvest planning (Chapter 5), forest-growth modeling (Chapter 6), and bioeconomic and market models (Chapter 9).

Several of the later chapters are concerned with systems that focus on the integration of information and knowledge. These are forest-growth models (Chapter 6), visualization and spatial analysis (Chapter 7), decision tools (Chapter 8), and bioeconomic and market models (Chapter 9). To varying degrees, these systems also are being applied to help formulate management actions intended to support sustainable forest management. We say "to varying degrees," because their role in decision support varies from indirect and implicit (e.g., forest-growth models) to direct and explicit (e.g., decision tools). Regardless of where each falls on the latter spectrum, however, the basic objective of each is not to *make* a management decision, but to organize and present information in such way as to *facilitate* management decisions. We think it is worth emphasizing that all modeling results should be approached with a healthy dose of skepticism. After all, as Box (1979) so famously noted, "All models are wrong; some models are useful" (p. 212). Similarly,

> It is not so much that we want to believe everything the computer tells us, but that we want a tool to confront us with the implications of what we think we know (Botkin 1977, pp. 217).

4. SOME IMPLICATIONS OF DIGITAL FORESTRY

In this volume, we have reviewed several major technologies that support the concept of digital forestry (Figure 13-2). Moreover, there is an almost bewildering array of specific computer-based systems that are currently available and relevant to the concept. We have discussed a number of these, but we have also barely scratched the surface, as it were, in terms of what is available. Although we admit there are almost certainly still gaps and deficiencies in current capabilities to support sustainable forestry, it is not so much lack of tools to do the work effectively that is the problem, as it is a lack of knowledge and experience within the management community with how to use them effectively. This is not intended in the least as a criticism of either forest managers or system developers. The current situation is entirely understandable in terms of the relative newness and complexity of the task itself, and the problem is further compounded by the number and relative newness of potentially useful systems.

So, perhaps we need digital foresters? And, no, we do not mean avatars! Rather, what we have in mind is the creation of forestry-based, but interdisciplinary, curricula that would offer forestry students broad exposure to all the relevant technologies, and, at least as importantly, a firm, holistic understanding of their collaborative application to sustainable forest management.

Simply learning to use the tools we already have at our disposal more effectively would almost certainly improve the ability of forest management organizations to implement sustainable forest management in the short term. However, in the longer term, there also is great potential for major gains through enhanced interoperability of systems (Thomson 2005). Interoperability has become one of the mantras of modern systems engineering, but there is a tendency to glibly offer it as the obvious solution. A system of interoperable systems that aims for reasonably comprehensive support of sustainable forestry poses an enormous challenge to the development community. Many of the modern systems discussed in this volume are complex systems in their own right, often requiring years of development.

The problem of designing for interoperability is the inherent complexity of what we seek to model, which Figure 13-2 only begins to hint at. It is extremely unlikely that we are presently in a position to describe in adequate detail what the specifications should be for an interoperable system of systems supporting sustainable forestry. How would one make a start? Gall (1986) cautions:

> A complex system that works is invariably found to have evolved from a simple system that worked… A complex system designed from scratch never works and cannot be patched up to make it work. You have to start over, beginning with a working simple system (Gall 1986, p. 58).

To the extent that this is true of systems, and this is well accepted in systems engineering generally (Booch 1994), then it is perhaps at least as apt when contemplating systems of interoperable systems. Progress toward effective interoperability will require a deliberate, evolutionary process. Think of it as a path from data to sustainable forests. We are already on the path, but we have a way to go. A new generation of forest managers, skilled in the collaborative application of the various necessary technologies, and whom we have called digital foresters, will be needed to lead the way.

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