Hiroshan Hettiarachchi
Reza Ardakanian *Editors*

Environmental Resource Management and the Nexus Approach

Managing Water, Soil, and Waste in the Context of Global Change

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ISBN 978-3-319-28592-4 ISBN 978-3-319-28593-1 (eBook)
DOI 10.1007/978-3-319-28593-1

Library of Congress Control Number: 2016936795

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG Switzerland

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Chapter 1
Managing Water, Soil, and Waste in the Context of Global Change

Hiroshan Hettiarachchi and Reza Ardakanian

Abstract This is an introductory chapter to the book. It provides the background and brief discussion on how and why resource management efficiency should be improved and how the proposed nexus approach may help. It provides a definition to the nexus approach applied to the water-soil-waste context. It also discusses how the negative impacts from some global change aspects can be overcome with nexus thinking.

1 Background

Despite all advances we have seen in the food and agriculture industries, one in seven people still goes to bed empty stomach (Lal 2014). Feeding seven billion mouths has already proven to be challenging, but the prediction is that this number will be increased by another two billion within the next 35 years (UN 2013). This situation certainly gives a warning on the way we currently address food security. The question in short is if we are using all potential solutions. Perhaps resource efficiency could play a larger role than what we think of it now.

Before getting into the discussion on solutions, it is worthwhile to understand why and how food has become an issue. The period between 1950 and 1970 marked a clear shift in the way we do "business" as mankind. Population doubled since then. Urban population exceeded rural population for the first time (Hoff 2011). New technologies flourished. New industries found their way into existence increasing the energy needs. The increase in global trade was sixfold (WTO 2008). The increase in water use and river damming was also sixfold (Xu et al. 2007). As a result, about 70 % of the world's freshwater resource is now used for agriculture (WBCSD 2005; USGS 2015). All these reasons have somehow contributed toward the food issue. It is not that we did not attempt to address food security. But whatever the change that has been happening since the 1950s is happening faster

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H. Hettiarachchi, R. Ardakanian (eds.), *Environmental Resource Management and the Nexus Approach*, DOI 10.1007/978-3-319-28593-1_1

than we can react. With all these facts in place, now we understand one thing clear; the change, which we now know as global change, is not only real, it is also accelerating its pace.

What is global change? In general, the planetary-scale changes that can make significant impact on Earth system are referred to as global change. The land, ocean, atmosphere, life, the planet's natural cycles, and deep Earth processes are the major components of the Earth system (IGBP 2015). Each of these components exists in a dynamic equilibrium with one another, and any significant change in one can result in changes (often negative) in others. Global change is not new. It has been happening for millennia. As a species, mankind has been adapting to all changes happening around them for hundreds of thousands of years. What's new is that, this time, the changes are happening fast. This demands us to find ways to cope up with the accelerated pace of global change. We, as humans, as always, begin to pay attention to any issue only when we feel the impact. With some serious signs of change such as increasing sea levels, more droughts, and changing rain patterns, if there is any right time to pay more attention, it is now.

2 Global Change Adaptation

Thirty years ago acceleration of global change was only a theory; now we know it is real. Currently there is much debate on how we should adapt to global change. With the effects of global change accelerating, adaptation should be required virtually in all regions of the globe. Adaptation to global change may involve adjustments or responses to actual or expected events or their effects. While no clear measuring stick is found to understand if we, as a society, have done a good job with adaptation, the ongoing discussions have undoubtedly raised the awareness. Thanks to these discussions, "global change" is now in the common vocabulary of many and a phenomenon understood by many.

The fivefold increase we witnessed in fertilizer use since the 1960s and also manufactured reactive nitrogen from fertilizer exceeding the global terrestrial production of reactive nitrogen are all signs of how we have tried to cope up with some changes (Lal 2014; UNEP and WHRC 2007). Feeding a population of seven billion people would not be possible without artificial fertilizers. Can the scientific advances and the engineering innovations in agriculture alone provide solutions to the expected future demand for food? In addition to the sciences and engineering, there is a whole range of other factors we need to take into consideration. A diverse range of adjustments to management models, human behavior, and public policy are among the other major aspects that need to be considered for adaptation (JGCRI 2015). Thinking outside the box is essential to finding effective solutions to an issue which is challenging and complicated. One helpful starting point is to revisit the management models and tools used in optimizing resource efficiency.

3 Water, Soil, and Waste

What we recommend is taking a second, but serious, look at how we manage our water, soil, and waste resources. Essentially, these are three key environmental resources involved in crop-based food production. Water is a natural resource that is important to a variety of stakeholders representing many different uses. The role played by soil in our day-to-day activities, and especially in food production, is also readily understood. They are both natural resources, and until we realized otherwise lately, these two resources have been taken for granted for their abundance. On the other hand waste is completely different from the above two. As a society we often look at waste only as a nuisance and a "problem." But it is in fact a man-made resource. The value is not readily visible as material is mixed in different proportions such as in a low-grade deposit of iron ore. For example, municipal solid waste (MSW) is rich in organics, although the proportion varies from place to place. With appropriate technological solutions, the organic fraction of MSW can be completely diverted from waste stream to the soils as compost or a soil conditioner.

Thus far "integrated management" options have been the most favorable tools used to manage environmental resources such as water, soil, and waste. Integrated water resource management (IWRM) is one of such example. While a city government is interested in how potable water is distributed and wastewater is collected efficiently within its boundaries, industries outside of the city need to coordinate with another local government body to arrange their water needs. In the meantime, the federal government of the same country might be engaged in negotiations with neighboring countries on how they should share one river to obtain water for agriculture as well as energy production. The need for managing water resources collectively, by different stakeholders, paved the way to this management option that we call IWRM today. The idea is to coordinate development and management of water-related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability (GWP 2000).

IWRM has been a helpful management model. However, like many other integrated management tools, IWRM also has one major weakness that limits its applicability and acceptance among the policy makers. While managing the main resource in concern, it often disregards the interdependencies the main resource may have with other recourses. Actions taken in managing one resource can make a positive or negative impact on another. Wastewater management is one of the best examples to explain how the above three resources are linked to each other. Proper management of wastewater provides not only a secondary source of water for some specific use but also nutrients that can be fed back to the soils.

The question is if we have the management "tools" and "mind-set" ready to capitalize on these synergies. The answer as of today is no. Sludge is just a by-product the wastewater treatment plant needs to get rid of, and in some countries, they are disposed in landfills. On the other hand, water sector rarely looks at wastewater as a legitimate supply source, except for some rare examples such as the NEWater project in Singapore (PUB 2015). The solution we propose is a formal mechanism to utilize theses synergies, which may not be achieved until the management of these three resources is also integrated. Integrated management at such higher level that goes beyond resource boundaries is certainly a new idea. We define it as the nexus approach.

4 The Nexus Approach

As per the Oxford Dictionary, a complicated series of connections between different things is referred to as a nexus (Oxford Dictionary 2015). In the management sense, nexus approach would mean managing more than one, complicated, and interconnected things to achieve better results. In a nutshell the nexus approach should provide a platform to look at more than one resource at a time in one nexus. Although universal acceptance to the nexus approach is yet to be gained, the concept itself is not exactly new. In connection with environmental resource management, the term nexus was introduced for the first time during the 1980s, notably in a project by the United Nations University on Food-Energy Nexus Programme (Sachs and Silk 1990). Resource management circles throughout the world continued to use the nexus concept to explain the interdependencies between different recourses in 1980s and 1990s. Some examples of these nexuses included water-electricity, water-energy, groundwater-electricity, water-agriculture, and finally water-energy-food.

However, the nexus approach only gained momentum and became popular among the international academia and policy circles in the lead up to the Bonn 2011 conference on the “Water, Energy, and Food Security Nexus.” The conference clearly argued that such an approach would result in improved water, energy, and food security by integrating “management and governance across sectors and scales” (UNU-FLORES 2015). It also pointed out that this approach would reduce trade-offs, build synergies, and promote sustainability and provide transition to a green economy (Hoff 2011).

The Bonn 2011 conference also discussed the need to have more integrated policy and decision making in all sectors involved and also the need for a coordinated and harmonized nexus knowledge base (Hoff 2011). This explains one characteristic feature of the nexus approach. Since nexus approach is about putting few disciplines into one action plan, the success depends on how the approach is supported by new and favorable policies. This has made governance and capacity development inclusive parts of nexus approach. Implementation to accommodate new changes would not be possible without them. Such new approaches certainly involve increased costs, but it is fair to say that expected future savings through nexus approach would be much higher.

In a previous section we briefly mentioned the challenges observed in the integrated management models and hesitation in the policy circles to accept some results produced by integrative management tools/models. It is also worthwhile to briefly discuss the reasons and how it does not become an issue in the nexus approach. Going back to the IWRM example, we know that the key variable is allocation of water. All other aspects of water users (energy, agriculture, industries, etc.) remain in the equations as fixed constraints, where they should also be treated variables in reality. Not being able to capture the reality, sometimes, leads to less favorable results. Decision makers are reluctant or sometimes completely unable to implement the recommendations made based on such integrated modeling tools.

As far as the modeling part is concerned, the major difference between integrated management and nexus approach is that in the nexus approach, the traditional input-output models are replaced by the concept of linked cycle management. Therefore, the model results should be much closer to reality compared to the models developed based on integrated approach. We do agree that this is easier said than done. The development of nexus approach-based modeling tools is yet another challenge to be addressed in the years to come.

5 Climate Change, Urbanization, and Population Growth

As briefly discussed in the first section of this chapter, there are many scientific aspects that lead to the discussion on global change. While some aspects are the results of global change, there are others that contribute to the acceleration of the same. We identify climate change, urbanization, and population growth as three of the most prominent aspects that can make significant impact on environmental resource management, especially water, soil, and waste.

Unusually long-lasting changes in weather patterns are referred to as climate change. The period of changes may vary from decades to as long as millions of years. When the World Climate Research Programme (WCRP) was established in 1980, there were so many “if” questions such as if the climate was really changing, if human activities are at least partly responsible for those changes, and also if the changes could be predicted. Few years later scientists discovered that the changes in the climate are in fact part of a big puzzle that we now call global change.

Climate change is believed to be caused by factors such as biotic processes, plate tectonics, volcanic eruptions, and variations in solar radiation received by Earth (USEPA 2015). Certain human activities are also considered as contributing factors toward some climate change components such as global warming. The Intergovernmental Panel on Climate Change (IPCC) recently revealed in a report that scientists are more than 95 % certain that most of global warming is caused by increasing concentrations of greenhouse gases and other anthropogenic activities (IPCC 2014). Global greenhouse gas emission from the food-related industries is only second to energy and heat production. Agriculture along contributes 14 % and other land use changes and forestry contribute 17 % (IPCC 2007). On the other hand, both soil and water are considered to be among the most climate-vulnerable sectors among environmental resources. Climate change causes further drying of already arid zones, and also extreme weather events result in less productive yield in crops. The whole world anticipates climate change adaptation to be the solution.

However, climate change adaptation is also proven to be costly. If irrigation is the solution for water scarcity, it should be noted that irrigation always cost more money compared to rain-fed agriculture. Desalination or tapping into deep groundwater is also much costlier than the use of conventional water supplies.

While climate change is more or less a result of global change, urbanization is a main driver of the cause. As mentioned before, city dwellers are now more than 50 % of the global population and this figure is expected to reach 70 % by year 2050 (Hoff 2011). This rapid increase in urbanization undoubtedly brings more challenges into the resource management equations which demand for new solutions to increase resource efficiency. Based on the monetary and technological capabilities, urban areas, if combined with nexus thinking, have the capacity to convert this threat to an opportunity. For example, the increased volume of waste and wastewater generated by the increased population can become a source of nutrients and a secondary source of water.

Similar to urbanization, population growth is also a driver of global change. The trend in the growth is clear; global population will reach nine billion by the middle of the century. What is not so clear is the impact it may make on environmental resources, especially the ones that are essential to food, water, and biomass production to sustain the increase in the population. In many developing countries, population is growing much faster than their food supplies. It is also known that the population pressures have resulted in degrading a large area of arable land.

6 The Way Forward

The nexus approach is still a new concept and is constantly evolving. Like many other new concepts, it is natural not to have a common consensus on the nexus approach. Many understand it, value it, but also have slightly different views on it. The application of nexus approach to manage environmental resources, especially water, soil, and waste, is a new experiment. But, it is an experiment that shows promising prospects.

The intention of this book is to provide a platform to discuss different viewpoints related to the nexus approach when applied to environmental resource management and how it may help us adapt to the rapid pace of global change. While this introductory chapter provides a brief but broad overview, the subsequent chapters present the perspectives of a number of thought leaders. They discuss how the nexus approach could contribute to management of water, soil, and waste. We believe this book will provide a clear and unbiased opinion on the role of the nexus approach in environmental resource management. We also believe that this will finally help shape the much needed nexus thinking for the future.

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Part I
Climate Change Adaptation

Chapter 2
Climate Change Impacts and Adaptation in Water and Land Context

Zbigniew W. Kundzewicz

Abstract Risks of climate change impacts on water and land have affected natural and human systems and are projected to increase significantly with increasing atmospheric greenhouse gas concentrations. There are key risks, spanning sectors, and regions. We can adapt to climate change impacts or mitigate the climate change. Prospects for climate-resilient sustainable development are related fundamentally to what the world accomplishes with climate change mitigation. Greater rates and degrees of climate change increase the likelihood of exceeding adaptation limits and make satisfactory adaptation much costlier and difficult, if not impossible. Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, particularly among water, energy, land use, and biodiversity. Adaptation and mitigation choices have implications for future societies, economies, environment, and climate in the long term. Responding to climate-related risks involves decision making in a changing world, with continuing uncertainty about the severity and timing of climate change impacts and with limits to adaptation.

1 Introduction

It is virtually certain that Earth's climate has warmed and it is very likely that most of the warming within the last 50 years has been due to anthropogenic emissions of greenhouse gases and carbon dioxide in particular (IPCC 2013). Climate change has been detected in observation records, and further, faster warming is projected in the future. Despite all the uncertainty in model-based projections, a robust conclusion can be drawn that the higher the greenhouse gas concentrations (and the resulting warming and accompanying effects), the more disadvantageous the aggregate, global impacts will be.

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H. Hettiarachchi, R. Ardakanian (eds.), *Environmental Resource Management and the Nexus Approach*, DOI 10.1007/978-3-319-28593-1_2

What information on climate change do we need to manage the resources of water, soil, and waste is a tricky question. Practitioners of water, soil, and waste management often declare needs for information that cannot be provided by the science at the present time, such as crisp, quantitative, values of credible projections for the future. Nevertheless, one can manage the resources under a great uncertainty of future precipitation projections that may be irreducible. Hence, the governance of climate change adaptation is of considerable importance as is comparison of experiences of diverse sectors and regions.

2 Information on Climate Change Impacts on Water and Land

2.1 Observed Changes in Mean Values and Extremes

Warming of the climate system of Earth is unequivocal, and many of the changes, observed since the 1950s, have been unprecedented over previous millennia. The atmosphere and the ocean have warmed, sea ice and glaciers have shrunk, and sea level has risen.

Globally averaged combined land and ocean surface temperatures, for which many independent datasets exist (IPCC 2013), calculated assuming a linear trend, show a warming of 0.85 [0.65–1.06] °C, between 1880 and 2012 (Fig. 2.1). Each of the 15 years of the twenty-first century was among the 16 warmest years in that period and 2015 was globally the warmest year on record (beating the earlier record set by the year 2014).

Global mean surface temperature varies greatly between decades and years such that trends based on short-term records are very sensitive to the beginning and end dates. For instance, the warming over 1998–2012 was relatively weak, because this period began in a very warm year corresponding to a strong El Niño event. Hence, some authors question the global warming hypothesis and suggest that the trend is due only to natural variability (Cohn and Lins 2005) Ocean warming, especially in the 0–700 m layer, dominates the increase in energy stored in the climate system, accounting for more than 90 % of the energy accumulated between 1971 and 2010. Over the last two decades, the Greenland and Antarctic ice sheets have been losing mass, mountain glaciers have continued to shrink, and Arctic sea ice and Northern Hemisphere spring snow cover have decreased in extent. The extent of Northern Hemisphere snow cover has also decreased and permafrost temperatures have increased in most regions. In the Russian European North, a considerable reduction in permafrost thickness and areal extent has been observed.

The rate of sea level rise since the mid-nineteenth century has been higher than the mean rate of the previous two millennia. From 1901 to 2010, the global mean sea level rose by about 0.19 m. The mean annual rate of global averaged sea level rise was 1.7 mm year^{-1} between 1901 and 2010 and nearly twice as high, 3.2 mm year^{-1} between 1993 and 2010 (IPCC 2013).

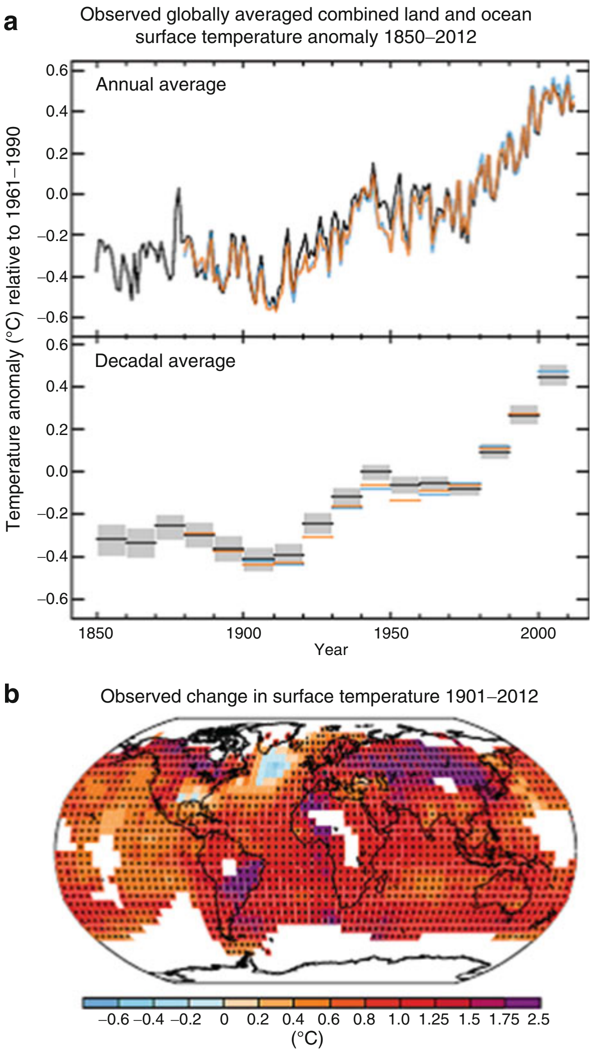

Fig. 2.1 (**a**) Observed global mean combined land and ocean surface temperature anomalies, from 1850 to 2012 from three datasets. *Top panel*: annual mean values. *Bottom panel*: decadal mean values including the estimate of uncertainty for one dataset (*black*). Anomalies are relative to the mean for 1961–1990. (**b**) Map of the observed surface temperature change from 1901 to 2012 derived from temperature trends determined by linear regression from one dataset (*orange line* in *panel a*). Trends have been calculated where data availability permits a robust estimate (i.e., only for grid boxes with greater than 70 % completeness of records and more than 20 % data availability in the first and last 10 % of the time period). Other areas are white. Grid boxes for which the trend is significant at the 10 % level are indicated by a + sign (Source: IPCC 2013)

Changes in many extreme weather and climate events have been observed. The frequency of warm extremes (e.g., number of warm days and nights, frequency of heat waves) has risen, while that of cold extremes (e.g., number of cold days and nights) has decreased (Field et al. 2012).

In contrast to the ubiquitous warming, there is less confidence in understanding changes in global precipitation (particularly in the first half of the twentieth century) largely due to insufficient data over large enough areas. Nonetheless, averaged over the mid-latitude land areas of the Northern Hemisphere, precipitation has increased since 1901, but confidence is medium before 1951 and high afterward. The probability of heavy precipitation events has increased over many areas. The frequency and intensity of heavy precipitation events have likely increased in North America and Europe.

However, the precipitation statistics are strongly influenced by variability among years, and there are problems with data reliability, particularly concerning snowfall. Observed changes of the timing, intensity, duration, and phase of precipitation are often weak and statistically insignificant. Apart from changes in precipitation, higher temperatures also contribute to changes in other components of the water cycle (e.g., higher evapotranspiration, impact on water quality). Water quality is influenced by temperature, which drives the reaction kinetics of key chemical processes, and accelerates weathering and nutrient cycling, and decreases equilibrium oxygen concentrations. Most biological processes including self-purification of rivers from gross organic pollution are influenced by oxygen concentrations.

In addition to climate, freshwater resources and water fluxes are controlled by population changes and economic development. Many river basins experience massive modifications of both land and freshwater resources for provision of shelter, food, fiber, fodder, and fuel. There have been changes in land use and in land cover, from urbanization, deforestation or afforestation, intensification or extensification of agriculture, mining, and compression of soil layers. Furthermore, humans attempt to smooth the variability of river flow with storage reservoirs (capturing water when abundant and releasing it in times of scarcity) and water transfer schemes. The runoff regime of many rivers differs greatly from the natural situation. Irrigation is by far the most prolific water use, being responsible for about 70 % of global water withdrawal and over 90 % of consumptive water use. The global irrigated area (about 19 % of global agricultural land) has been increasing. Requirements for food security are a driver for the trend in irrigation water use.

Variation in streamflow reflects variations in atmospheric conditions—primarily, changes in precipitation (volume, timing, and phase) and changes in evapotranspiration (dependent on atmospheric CO_2 concentration, temperature, energy availability, atmospheric humidity, and wind speed), changes in land use (catchment storage, extent of impermeable area, forested, and agricultural land), and more direct human regulation of the water cycle (dike and dam building, irrigation, and drainage) (Gerten et al. 2008).

Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones, and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability. Climate-related hazards may exacerbate other stresses, with increased problems for livelihoods, especially of poor people.

2.2 Attribution of Change

Attribution of climate change is relatively straightforward. Warming over land has been found unambiguous. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2013) notes that: “It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together." This is a stronger statement than in earlier IPCC reports (Kundzewicz 2014) and is consistent with much evidence.

Greenhouse gas contribution to global mean surface warming is likely in the range of 0.5 °C to 1.3 °C between 1951 and 2010, with contributions from other anthropogenic forcings, including the cooling effect of aerosols, likely in the range of −0.6 °C to 0.1 °C. The contribution from natural forcings is likely to be in the range of −0.1 °C to 0.1 °C, i.e., much less than the contribution from anthropogenic forcings, and the contribution from natural internal variability is likely to be in the range of −0.1 °C to 0.1 °C (IPCC 2013).

Atmospheric concentrations of the greenhouse gases: carbon dioxide (CO_2)—responsible for most of the increase in the greenhouse effect, methane (CH_4), and nitrous oxide (N_2O) have all increased considerably since 1750 due to human activity. In 2011, they exceeded the preindustrial levels by about 40 %, 150 %, and 20 %. Greenhouse gas concentrations are now substantially higher than ever before during the past 800,000 years.

It is very likely that anthropogenic forcings have made a substantial contribution to increases in global upper ocean heat content (0–700 m). Human influence has also been detected in changes in the global water cycle (observed increases in atmospheric moisture content, global-scale changes in precipitation patterns over land, and changes in salinity), in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes (e.g., intensification of heat waves and heavy precipitation over land). Black carbon emissions affect glacier albedos and melt rates.

Natural and anthropogenic substances and processes that alter the Earth's energy budget are drivers of climate change. Radiative forcing (RF) quantifies the change in energy fluxes caused by changes in these drivers since the preindustrial times. Positive RF leads to surface warming; negative RF leads to surface cooling.

The best estimate for the total anthropogenic RF for 2011 relative to 1750 is 2.29 W m^{-2}. It is a combination of continued growth in most greenhouse gas concentrations and a cooling effect (negative RF) due to aerosols. The RF from changes in concentrations in greenhouse gases (CO_2, CH_4, N_2O, and halocarbons) is 2.83 W m^{-2}, with 1.68 W m^{-2} from CO_2 alone. The RF of the total aerosol effect in the atmosphere, which includes cloud formation due to aerosols, is −0.9 W m^{-2}. Aerosols and their interactions with clouds have offset a substantial portion of global mean forcing from greenhouse gases. The total natural RF from solar irradiance changes and stratospheric volcanic aerosols made only a small contribution to the net radiative forcing, except for brief periods (months to a few years) after large volcanic eruptions.

For detection and attribution of change, important for our understanding and taking of measures, we need long series of records of consistently good quality data. However, there are problems within the availability and quality of hydrological data. Knowledge of baseline conditions is rare and human influence is typically strong through river regulation, deforestation, urbanization, dams, and reservoirs. In order to detect a weak, if any, climate change component in river flow, it is necessary to eliminate other influences and use data from pristine (baseline) river basins (Kundzewicz and Schellnhuber 2004).

The hitherto relatively weak climate change signal is superimposed on a high natural variability of rainfall and river flow (under a confounding effect of land use change). According to Wilby et al. (2008), in some basins, statistically significant trends in river flow are unlikely to be found for several decades more. A robust finding though is that warming leads to changes in the phase of winter precipitation (more rain at many locations) and changes in seasonality of river flows in river basins where much winter precipitation still falls as snow, with spring flows decreasing because of trends toward reduced or earlier snowmelt and winter flows increasing (snowmelt may contribute to winter rather than spring flow).

The global water system is very complex, so that it is difficult to disentangle individual contributions of various factors to changes in freshwater variables (Döll et al. 2014). Gerten et al. (2008) carried out a model-based study that attributed changes in global river discharge in the twentieth century. Variations in precipitation were the main factor. Important also were temperature effects on evapotranspiration and partly compensating effects of rising atmospheric CO_2 concentration on the physiology and abundance of vegetation. Physiological effects include reduced stomatal aperture, thus reduced leaf transpiration, due to increased water use efficiency, and the structural effects of increased biomass production and/or spreading of the vegetation, and thus increased evapotranspiration. The attribution of sea level rise is as follows (IPCC 2013). Between 1993 and 2010, the global mean sea level rise has been approx. 3.2 mm $year^{-1}$. This is a bit more than the sum of the estimated contributions from ocean thermal expansion due to warming (1.1 mm $year^{-1}$), melting of glaciers (0.76 mm $year^{-1}$), the Greenland ice sheet (0.33 mm $year^{-1}$), the Antarctic ice sheet (0.27 mm $year^{-1}$), and land water storage (0.38 mm $year^{-1}$).

2.3 Projections of Mean Values and Extremes

Models simulate climate change on the basis of a set of scenarios of anthropogenic forcings and indicate that continued emissions of greenhouse gases will cause further warming and corresponding changes in all components of the climate system. Substantial and sustained reductions of greenhouse gas emissions will be required to curb climate change.

According to recent projections (IPCC 2013), the global surface warming for 2016–2035 relative to 1986–2005 will be in the range from 0.3 °C to 0.7 °C, assuming no major volcanic eruptions or changes in total solar irradiance. For 2081–2100, temperature increase is projected in the range from 0.3 to 1.7 °C (for the RCP2.6 scenario, corresponding to an effective global climate policy that seems unlikely now) to 2.6–4.8 °C (for RCP8.5, corresponding to a failure of the global climate policy). For description of RCP (representative concentration pathways) scenarios, see IPCC (2013). Warming will continue to vary from year to year and will not be uniform regionally. Most aspects of climate change will persist for many centuries even if emissions of CO_2 are stopped—there is a substantial multi-century climate change commitment created by past and present emissions of greenhouse gases.

The Arctic sea ice cover will continue to shrink and thin and the Northern Hemisphere spring snow cover and global glacier volume will decrease further. The global mean sea level will continue to rise, at an increasing rate, due to warming and increased loss of mass from glaciers and ice sheets. The global mean sea level rise for 2081–2100 relative to 1986–2005 will likely be in the range from 0.26–0.55 m for the RCP2.6 scenario to 0.45–0.82 m for RCP8.5.

Projected changes in the global water cycle are not uniform. A general finding is that the contrast in precipitation between wet and dry regions and between wet and dry seasons will increase. Wet regions will likely become wetter and dry regions drier, in the warming world. This projected increase of variability leads to increase of flood and drought hazards in many areas. Decreased soil moisture and increased risk of agricultural drought are likely in presently dry regions. In contrast, renewable water resources (defined as long-term average annual streamflow) are likely to increase at high latitudes as well as in some currently water-stressed areas in India and China. However, annual streamflow increases may not alleviate water stress if they are caused by increases during the wet (monsoon) season or if no infrastructure is available to capture the additional volume of water. The fraction of the global population experiencing water scarcity and the fraction affected by major river floods are projected to increase with the level of warming.

Extreme precipitation events are projected to become more intense and more frequent in many parts of the world and may lead to more floods, landslides, and soil erosion. Soil erosion, simulated assuming a doubled CO_2 concentration, is projected to increase by about 14 % by the 2090s, compared with the 1980s (9 % attributed to climate change and 5 % to land use change), with increases by as much as 40–50 % in Australia and Africa (Jiménez et al. 2014). The largest increases are expected in semiarid areas, where a single event may contribute 40 % of total annual erosion. Climate change will also affect the sediment load in rivers. Increases in total and intense precipitation, increased runoff from glaciers, permafrost degradation, and the shift of precipitation from snow to rain will further increase soil erosion and sediment loads in colder regions.

Some climate change impacts can be regionally positive (less energy consumption in warmer winters, opening up new arable lands and new sea transport routes). However key risks associated with the warming (cf. Fig. 2.2) constitute tough challenges for less developed countries and vulnerable communities, given their limited ability to cope. Throughout the twenty-first century, climate change impacts are projected to slow down economic growth, make poverty reduction more difficult, further erode food security, and prolong existing and create new poverty traps (IPCC 2014).

Global economic impacts from climate change are difficult to estimate. Estimates vary in their coverage of economic sectors and depend on many disputable assumptions. With these limitations, the preliminary and incomplete estimates of global annual economic losses for additional warming of 2 °C are between 0.2 and 2.0 %

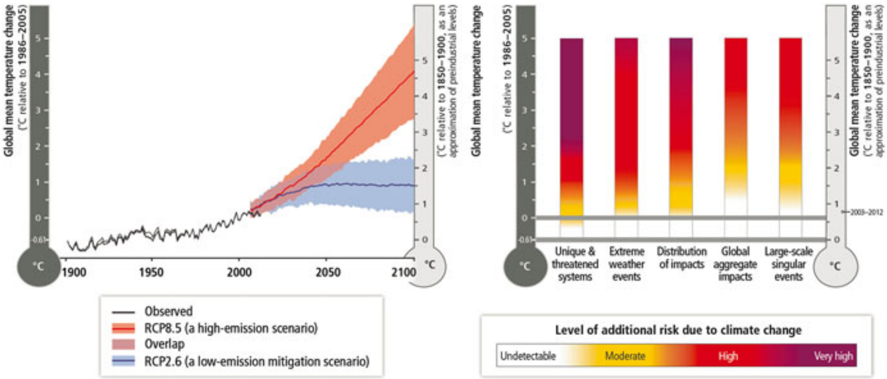

Fig. 2.2 A global perspective on climate-related risks. Risks associated with reasons for concern are shown at *right* for increasing levels of climate change. The color shading indicates the additional risk due to climate change when a temperature level is reached and then sustained or exceeded. Undetectable risk (*white*) indicates no associated impacts are detectable and attributable to climate change. Moderate risk (*yellow*) indicates that associated impacts are both detectable and attributable to climate change with at least medium confidence, also accounting for the other specific criteria for key risks. High risk (*red*) indicates severe and widespread impacts, also accounting for the other specific criteria for key risks. *Purple*, introduced in this assessment, shows that a very high risk is indicated by all specific criteria for key risks. For reference, past and projected global annual average surface temperature is shown at *left* (as in IPCC 2013) (Source: IPCC 2014)

of income. If costs related to health impacts and social problems are internalized, the loss is higher. Nevertheless, it is a robust finding that losses accelerate with greater warming.

2.4 Gaps in Knowledge and Uncertainties

Present understanding of climate change and its impacts suffers from strong uncertainties because of lack of knowledge and understanding of the processes, their complexities, and connections.

To support water management in a changing climate, quantitative measurements are needed. These involve use of a chain of methods or models, the output of which is subject to significant uncertainty. The first uncertainty is related to scarce information about the current or reference state of the system under consideration.

If only short hydrometric records are available, the full extent of natural variability can be understated. Data on water use, water quality, groundwater, sediment transport, and aquatic ecosystems are also scarce, and climate change impacts on them and their interaction with the biosphere are not adequately understood. In current models, precipitation, the principal input, is not adequately simulated, and we cannot reconstruct the recorded precipitation in the observation period with satisfactory accuracy. Improvement of various aspects of modeling and the use of data, as well as better integration of climate change modeling and impact modeling is needed, and this requires solving difficult problems related to a mismatch in scale between models (large grid cells in climate models versus much smaller grid cells in hydrological models).

The lack of information is critical in developing countries. More monitoring stations are needed but networks are often shrinking for economic reasons. There remains also a challenge in attributing observed or simulated changes in freshwater resources to the drivers that may have caused these changes (Kundzewicz and Gerten 2015).

There are many sources of uncertainty in projections of the future water cycle. Uncertainty stems from the internal variability of the climate system and from forcings of the climate system, like increased atmospheric emission of greenhouse gases, dependent on socioeconomic development and effectiveness of climate change mitigation (in reducing greenhouse gas concentrations), solar and volcanic influences, and changes of land use. Evaluation of the effects of forcings on climate by global climate models (each with different model sensitivities) and then downscaling and bias-correcting the output of the global climate models are further important sources of uncertainty. The next source of uncertainty is related to translation of climate change projections into impact projections. Finally, there is uncertainty connected with adaptation. The uncertainty related to future social and economic development is considerably amplified along this chain; for the same emission scenario, different models may produce largely different impacts. This difference is often larger than that arising in one model with different emission scenarios. Climate models, downscaling/bias-correction methods, and hydrological models may contribute comparable amounts of uncertainty to impact assessments (Jiménez et al. 2014). Uncertainties in climate change projections increase with future time. In the near term, climate model uncertainties may play a more important role, because near-term climate is strongly conditioned by past greenhouse gas emissions, while over longer periods, uncertainties regarding future greenhouse gas emission scenarios become increasingly significant (IPCC 2013). Finally, uncertainty regarding future socioeconomic conditions, affecting future vulnerability and exposure, and uncertainty about responses of interlinked human and natural systems are at least as large as the climate-related uncertainty.

For precipitation changes until the end of the twenty-first century, uncertainty caused by the selection of a model and a selection of emission scenario (concentration pathway) is high (Kundzewicz et al. 2007; 2008). The confidence in the magnitude of projected precipitation change (and—over some regions—even in the sign of change because over large areas, climate models disagree as to the direction of change of future precipitation) is low. The methodology is not adequate and further work is needed (Kundzewicz and Stakhiv 2010). Downscaling cannot compensate for the basic inadequacies of the climate models. The issue of applicability and credibility of GCM results generates a vigorous scientific debate (Koutsoyiannis et al. 2009; Anagnostopoulos et al. 2010; Wilby 2010).

Consequently, quantitative projections of changes in streamflow remain largely uncertain in many regions. In high latitudes and parts of the tropics, climate models are consistent in projecting future precipitation increase, while in some subtropical and lower mid-latitude regions, they are consistent in projecting precipitation decrease. Between these are areas with high uncertainty, where the current generation of climate models does not agree on the sign of runoff changes (Kundzewicz et al. 2007, 2008).

Traditionally, but incorrectly, the measure of uncertainty has been equated with the range of projections, and confidence was assessed through simple counting of the number of models that shows agreement in the sign of a specific climate change. It was assumed that the greater the number of models in agreement, the greater the robustness, but this stance has shortcomings. However, since the change is controlled by processes that are not well understood and validated in the present climate, large errors in the projections are likely.

The current approach for dealing with climate model and impact model uncertainties is to perform studies where the output of several climate models is used as input to one or, better, to several hydrological models to produce an ensemble of potential changes in risk. Multi-model studies typically assume that each combination of climate model and hydrological model runs should be given the same weight (Döll et al. 2014). Very large numbers of scenarios are used by some authors to generate likelihood distributions of indicators of impact for use in risk assessment. However, there is indeed a “deep” uncertainty, because analysts do not know, or cannot agree upon, how the climate system and water management systems may change, how models represent possible changes, or how to value the desirability of different outcomes, cf. Jiménez et al. (2014).

Among the burning research needs are those aimed at reducing uncertainty in understanding, observations, and projections of climate change, its impacts, and vulnerabilities (Kundzewicz and Gerten 2015), in order to better assist water resources planners in their duty to adapt to change. However, after a call to reduce uncertainty issued in the IPCC First Assessment Report in 1990, major funds, equivalent to billions of US$, have been spent worldwide aimed at reducing uncertainties. Despite these major efforts, uncertainties in projections of future changes have actually grown, even if characterization of uncertainty has improved, i.e., unknown unknowns have turned into known unknowns. Trenberth (2010) phrased it: “More knowledge, less certainty.” We know increasingly well that we do not know well enough.

2.5 Impacts on Sectors and Systems Related to Water and Land

There is a range of key risks, spanning sectors, and regions. There is a risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small islands, owing to storm surges, coastal flooding, and sea level rise, as well as risk for large urban populations due to inland flooding in some regions. Extreme weather events may lead to breakdown of infrastructure networks and critical services. Extreme heat waves are likely to increase risk of mortality and morbidity, particularly for vulnerable urban populations and those working outdoors. Extreme climate events exacerbate risk of food insecurity and the breakdown of food systems, particularly for poorer populations, as well as risk of loss of rural livelihoods and income owing to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly in less developed semiarid regions. There is also a risk of loss of ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods (IPCC 2014).

Risks of climate change impacts on water and land have affected natural and human systems and are projected to increase significantly with increasing greenhouse gas concentrations. In many regions, changing precipitation or melting snow and ice have altered hydrological systems and water resources. Climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions, exacerbating competition among the water users and sectors, i.e., agriculture, ecosystems, settlements, industry, and energy producers.

Many species have shifted their geographical ranges, seasonal activities, migration patterns, abundances, and species interactions in response to climate change. A large fraction of both terrestrial and freshwater species face increased extinction risk under projected climate change, especially as climate change interacts with other stressors, such as habitat modification, overexploitation, pollution, and invasive species. There is a high risk of abrupt and irreversible regional-scale change in the composition, structure, and function of terrestrial and freshwater ecosystems, including wetlands, within this present century.

Owing to sea level rise, coastal systems and low-lying areas will increasingly experience adverse impacts such as land submergence, coastal flooding, and coastal erosion. Many global risks of climate change are concentrated in urban areas, where more than 52 % of the global population lived in 2011 and this proportion is expected to grow further.

Negative impacts of climate change on crop yields have been more common than positive impacts. Rapid food and cereal price increases following climate extremes in key producing regions indicate such sensitivity. Climate change has reduced wheat and maize yields for many regions and overall. For the major crops, such as wheat, rice, and maize, in tropical and temperate regions, climate change without adaptation is projected to reduce production for local temperature increases of 2 °C or more above late-twentieth-century levels, although individual locations may benefit. Major future rural impacts are expected on water availability and supply, food security, and agricultural incomes, including shifts in crop production areas across the world.

Water demand and use for food and livestock feed production are governed not only by crop management and its efficiency but also by the balance between atmospheric moisture deficit and soil water supply. Thus, changes in climate (precipitation, temperature, radiation) will affect the water demand of crops grown in both irrigated and rain-fed systems (Jiménez et al. 2014). Irrigation demand is projected to increase significantly in many areas (by more than 40 % across Europe, the USA, and parts of Asia) and often to exceed local water availability.

Where poor soil is not a limiting factor, physiological and structural crop responses to increased atmospheric CO_2 concentration (CO_2 fertilization) might partly cancel out the adverse effects of climate change, potentially reducing global irrigation water demand (Jiménez et al. 2014). However, even in this optimistic case, increases in irrigation water demand are still projected under most scenarios for some regions, such as southern Europe. The CO_2 effects may thus lessen the total number of people suffering water scarcity; nonetheless, the effect of anticipated population growth is likely to exceed those of climate and CO_2 change on agricultural water demand, use, and scarcity (Gerten et al. 2011). Rain-fed agriculture is vulnerable to increasing precipitation variability and differences in yield, and yield variability between rain-fed and irrigated land may increase.

Climate change will exacerbate future health risks given regional population growth and vulnerability due to pollution, food insecurity in poor regions, and existing poor health, water, sanitation, and waste collection systems (Field et al. 2014). Projected climate change will impact upon human health by exacerbating problems that already exist but will also lead to increases in ill-health in many regions and especially in less developed countries. Warmer winters will lead to less morbidity and mortality (freezing to death) in moderate and cold climates, but impacts from such extreme climatic events, as heat waves, droughts, floods, and wildfires, are projected to result in more deaths and to worsen mental health and human well-being. There is a greater likelihood of injury, disease, and death due to more intense heat waves and fires, increased likelihood of undernutrition resulting from diminished food production in poor regions, risks from lost work capacity and reduced labor productivity in vulnerable populations, and increased risks from food- and waterborne diseases. Climate change will increase demands for healthcare services and facilities.

Several climate change impacts are of concern to water utilities (Jiménez et al. 2014). Climate change may lead to decrease of natural storage and availability of water (hence to increasing need for artificial water storage) and to increased water demand, hence competition for the resource. Higher water temperatures encourage algal blooms and possible increased risks from cyanotoxins and natural organic matter in water sources, requiring additional or new treatment of drinking water. Possibly drier conditions increase pollutant concentrations, while increased storm runoff increases loads of pathogens, nutrients, and suspended sediment. Saline intrusion due to excessive water withdrawals from aquifers may be exacerbated by sea level rise, leading to reduction of freshwater availability, in particular where groundwater recharge is also expected to decrease. Even a small sea level rise may cause very large decreases in the thickness of the freshwater lens below small islands (cf. Kundzewicz et al. 2008).

For sewage, there are three climatic conditions of particular importance. Heavier rainstorms imply the need to treat additional wastewater in combined sewer systems for short periods. Current design rules, based on critical "design storms" defined through analysis of historical precipitation data, will need to be modified. Dry weather brings other risks. Soil shrinks as it dries, causing water mains and sewers to crack and making them vulnerable to contact with wastewater. Finally, sea level rise leads to intrusion of brackish or salty water into sewers and necessitates processes that can handle saltier wastewater.

Climate change will displace people and can indirectly increase risks of violent conflicts by amplifying well-documented drivers of these conflicts, in particular poverty and economic shocks. The impacts of climate change on the critical infrastructure and territorial integrity of many states are expected adversely to influence national security. For example, land inundation due to sea level rise poses risks to the territorial integrity of small island states and to states with extensive coastlines. Some transboundary impacts of climate change, such as changes in shared water resources, have the potential to increase rivalry among states (Field et al. 2014).

Climate-related risks interact with other biological stresses (such as biodiversity loss, soil erosion, and water contamination) and with social stressors (such as inequalities, poverty, gender discrimination, and lack of institutions). For most economic sectors, the impacts of non-climatic drivers, such as changes in population, age structure, income, technology, relative prices, lifestyle, regulation, and governance, are projected to be large relative to the impacts of climate change.

3 Climate Change Adaptation

3.1 Adaptation Under Strong Uncertainty in Projections

The likelihood of deleterious impacts, as well as the cost and difficulty of adaptation, is expected to increase with magnitude and speed of global climate change (Stern 2006). Hence, effective mitigation of climate change is necessary to reduce the adverse climate change impacts. However, we are already committed to further warming (Wigley 2005) and corresponding impacts, even under the absurd assumption of an instantaneous freeze of greenhouse gas concentrations at present levels. It is therefore necessary to adapt to climate change impacts on water and land.

Climate change will affect current water management practices and the operation of existing water infrastructure, which are very likely to be inadequate to cope with the negative impacts of climate change on water. Traditionally, it has been assumed that the natural freshwater resource base is constant. Water resources systems have been designed and operated under the assumption of stationary hydrology, tantamount to the principle that the past is the key to the future. Now, the validity of this principle is challenged (Kundzewicz et al. 2007, 2008), “the stationarity is dead” (Milly et al. 2008), and the existing design procedures are not adequate for changing conditions. If a significant change in the severity of hydrological extremes is projected in the changing world, then existing procedures of designing dikes, spillways, dams, and reservoirs, polders, and bypass channels, traditionally based on the assumption of stationarity of river flow, have to be revisited. Otherwise, systems will be wrongly conceived, under- or overdesigned, resulting in either inadequate performance or excessive costs (e.g., of large safety margin). But adequate tools for nonstationary systems are not in place yet.

Climate change has introduced large uncertainties into the estimation of future freshwater resources. The impacts of climate change on freshwater systems, even under an assumed emission scenario, cannot be quantified in a deterministic way; we can only aim at providing a broad range of plausible projections (Kundzewicz et al. 2007, 2008). Hence the question may arise—"adapt to what?" Uncertainty in climate impact projections has implications for adaptation practices. Adaptation procedures need to be developed, which do not rely on precise projections of changes in river discharge, groundwater, etc. Owing to uncertainty, water managers should no longer base their decisions on crisp estimates of future hydrological conditions and their impacts, but consider instead future freshwater hazards and risks. This means that a broad range of possible future hydrological changes should be considered for managing water under climate change, taking into account a number of emissions and socioeconomic scenarios. It is difficult to assess water-related consequences of climate policies and emission pathways with high credibility and accuracy.

There is no doubt that better accommodation of extremes of present climate variability augurs better for management of the circumstances of future climate. Reducing present vulnerability and exposure to existing climate variability should be on the agenda for the immediate future, independently of the projections.

There are two alternative courses of action in the case of strong and possibly irreducible uncertainty: the precautionary principle and adaptive management. Since uncertainty in projections for the future is large, a precautionary attitude lends itself well for use in planning adaptation. The precautionary principle (resilient or "no-regrets" approach) is a variation of the min-max concept—to choose the approach which minimizes the worst outcome. As stated in the Rio Declaration, (#15), "the precautionary approach shall be … applied … Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent … degradation." An alternative approach is adaptive management and the use of scenarios, learning from experience, and the development of flexible and low-regret solutions that work satisfactorily within the range of plausible climate futures.

The large range of values for different climate model-based scenarios suggests that adaptive planning should be based on ensembles rather than being restricted to only one or a few scenarios. Hence, multi-model probabilistic approaches are preferable to using the output of only one climate model, when assessing uncertainty in climate change impacts. The broad range of different model-based climate scenarios suggests that adaptive planning should not be restricted to only one or a few scenarios, because there is no guarantee that the range of simulations adequately represents the full possible range (Kundzewicz et al. 2007, 2008). It is also widely recognized that improved incorporation of current climate variability into water-related management would make adaptation to future climate change easier. A first step toward adaptation to future climate change is therefore to reduce vulnerability and exposure to present climate through low-regret measures and actions emphasizing co-benefits.

Every flood dike is designed to withstand a flood of particular frequency, e.g., the 100-year flood, so it will be overtopped, breached, or washed away if a much higher flood occurs. The notion of a 100-year flood has to be revisited in the light of ongoing, and projected, changes. The 100-year flood for a past control period is unlikely to be of the same amplitude as the 100-year flood in a future period of concern. This is of importance for large water infrastructure (e.g., dikes, dams, and spillways). However, because of the large uncertainty of projections for the future, no precise, quantitative information can be delivered. Water managers in some countries (e.g., Germany, the UK, the Netherlands) already explicitly incorporate the potential effects of climate change into policies and specific design guidelines. They have introduced a "climate change factor," a safety margin based on climate change impact scenarios (in the absence of precise numbers), which is taken into account in any new plans for flood control measures. For example, measures to cope with the increase of the design discharge for the Rhine in the Netherlands from 15,000 to 16,000 m^3/s must be implemented by 2015, and it is planned to increase the design discharge to 18,000 m^3/s in the longer term, owing to expected climate change (Klijn et al. 2004).

The costs and benefits of adaptation, including damage avoided, are expected to be large, but are not adequately known. It is necessary to evaluate social and economic costs and benefits (in the sense of avoided damage) of adaptation, on several time scales. A serious challenge is to provide a better basis for decisions under uncertainty. Improved characterization of uncertainty and incorporating climate change information in managing risks could help water resource planners to adapt to uncertain future changes.

There are some intervention options which perform well under any of the alternative futures and others which perform extremely well in some but not in others. Some adaptation measures can be virtually no-regret (doing things that make sense anyway) or low-regret, but other measures may entail significant costs. Comprehensive estimates of costs of adaptation are limited and speculative. Even less is known about the benefits of adaptation, in terms of damages avoided. The implementation of very costly adaptation options whose performance depends critically upon a particular future should be delayed as long as possible. There is an urgent research need to develop methodology regarding decision making under high uncertainty. For example, improved characterization of uncertainty (joint analysis of ensembles of climate models) could help efforts to adapt to uncertain future hydrological changes. In addition, incorporating climate change information in a risk management approach to water resource planning would be useful.

Planning horizons and lifetimes for some adaptation options (e.g., dams) are up to many decades, during which information is expected to change. There is an opportunity cost of failure to act early vs value of delay and waiting for the range of uncertainty to become narrower. A serious policy dilemma exists. Unclear and uncertain impacts in a longer perspective could need heavy investment now. Is it rational to adapt now to the existing (strongly uncertain) projections or is it perhaps more advisable to wait for more accurate and trustworthy information and to adapt then (having possibly missed the opportunity of advanced adaptation)? Early adaptation is effective for avoiding damage, provided that projections of future climate change are sufficiently accurate. Delayed adaptation may lead to greater subsequent costs.

Water, soil, and waste management decisions have always been made on the basis of uncertain information. Yet, changes in climatic, terrestrial, and socioeconomic systems challenge the existing management practices by adding uncertainties and novel risks—often outside the range of experience. Adaptation, both reactive and anticipative, makes use of a feedback mechanism, implementing modifications (and possibly correcting past mistakes) in response to new knowledge and information. Approaches that are resilient to uncertainty are not entirely technical (or supply-side), and participation and collaboration among all stakeholders are central to adaptive water management.

3.2 Adaptation in Different Regions

Throughout history, people and societies have adjusted to and coped with weather, climate, climate variability, and extremes, with varying degrees of success. Adaptation practices included crop diversification, irrigation, water management, disaster risk management, and insurance, but climate change, along with other drivers of change, poses novel risks often outside the range of experience (Noble et al. 2014). Adaptation to climate change is now becoming embedded in planning processes and experience is accumulating. Mimura et al. (2014) noted that adaptation to climate change is moving from a phase of awareness to the construction of actual strategies and plans in societies.

Adaptation is highly place and context specific, with no single approach appropriate across all settings. Effective strategies take into account vulnerability and exposure and their linkages with development and climate change. Adger et al. (2007) listed types of adaptations in different regions. In Africa, examples included adaptation to sea level rise through adoption of a National Climate Change Action Plan (in Egypt) integrating climate change concerns into national policies. It regulated setback distances for coastal infrastructure and installation of hard structures in areas vulnerable to coastal erosion. Examples of adaptation to drought included expanded use of traditional rainwater harvesting and water conserving techniques, building of shelterbelts and windbreaks, monitoring of the number of grazing animals and cut trees, recreation of employment options after drought, capacity building of local authorities, creation of revolving credit funds, and assistance to small subsistence farmers to increase crop production.

In Asia and Oceania, adaptation to sea level rise, saltwater intrusion, and storm surges has been of great importance. It embraces, among others, reforestation of mangroves, construction of cyclone-resistant houses, retrofit of buildings to improved hazard standards, review of building codes, capacity building for shoreline defense system design, introduction of participatory risk assessment, provision of grants to strengthen coastal resilience, and rehabilitation of infrastructures.

Examples of adaptation to droughts and wildfires include shift to drought-resistant crops, use of shallow tube wells, rotation methods of irrigation during water shortage, construction of water-impounding basins, construction of fire lines and controlled burning, rainwater harvesting, leakage reduction, and bank loans allowing for purchase of rainwater storage tanks.

In the Americas, examples of adaptation to permafrost melt and change in ice cover given by Adger et al. (2007) included changes in livelihood practices by the Inuit, such as change of hunt locations, diversification of hunted species, use of GPS technology, and encouragement of food sharing. As regards adaptation to extreme temperatures, examples embraced implementation of heat health alert plans, which included opening of designated cooling centers at public locations, information to the public through local media, distribution of bottled water to vulnerable people, operation of a heat information line, and availability of an emergency medical service vehicle with specially trained staff and equipment. Adaptation to sea level rise included land acquisition for coastal lands damaged or prone to damage by storms, or of other land buffers; the acquired lands are being used for recreation and conservation. Adaptation to drought included adjustment of planting dates and crop variety (e.g., inclusion of drought-resistant plants), accumulation of commodity stocks as economic reserves, spatially separated plots for cropping and grazing to diversify exposures, diversification of income by adding livestock operations, setup/provision of crop insurance, and creation of local financial pools (as alternatives to commercial crop insurance).

In Europe, adaptation to sea level rise and floods includes a range of structural and nonstructural measures. An example of a large project is the Thames Barrier that is aimed to reduce the risk of flooding. Coastal realignment has been undertaken in the UK, converting arable farmland into salt marsh and grassland to provide sustainable sea defenses. Among other measures are use of sand supplements to coastal areas; improved management of water levels through dredging; widening of river banks, allowing rivers to expand into side channels and wetland areas; deployment of water storage and retention areas; conduct of regular reviews of safety characteristics of all protecting infrastructure; preparation of risk assessments for flooding and coastal damage in the coastal zone; identifying areas for potential inland reinforcement of dunes; and provision of guidance to policy makers. Adaptation to upward shift of the natural snow-reliability line and glacier melt includes artificial snowmaking, grooming of ski slopes, moving ski areas to higher altitudes and glaciers, use of white plastic sheets as protection against glacier melt, and diversification of tourism revenues (e.g., all-year tourism).

As noted by Noble et al. (2014), adaptation involves reducing risk and vulnerability, seeking opportunities, and building capacity to cope with climate impacts, as well as mobilizing that capacity by implementing decisions and actions. Adaptation needs can be categorized as biological, environmental, information, capacity, societal, financial, institutional, and technological.

Governments are starting to develop adaptation plans and policies and to integrate climate change considerations into broader development plans. Adaptation planning and implementation can be enhanced through complementary actions across different levels, from individuals to governments. Across regions, there are complementary roles in enabling adaptation planning and implementation, for example, through increasing awareness of climate change risks, learning from experience with climate variability, and achieving synergies with disaster risk reduction. The local government and the private sector are increasingly recognized as critical to progress in adaptation, given their roles in scaling up adaptation of communities and households and in managing risk information and financing. National governments can coordinate adaptation by local and subnational governments, creating legal frameworks, protecting vulnerable groups, and providing information, policy frameworks, and financial support. Public action can influence the degree to which private parties undertake adaptation (Field et al. 2014).

Because national governments decide many of the funding priorities and tradeoffs, develop regulations, promote institutional structures, and provide policy direction to district, state, and local governments, they are essential in advancing adaptation agenda. In developing countries, national governments are usually the contact point and initial recipient of international aid funds. National governments can help mobilize political will, support the creation and maintenance of climate research institutions, establish networks that share information, and may facilitate the coordination of budgets and financing mechanisms (Noble et al. 2014). Governments have the potential to directly reduce the risk and enhance the adaptive capacity of vulnerable areas and populations by developing and implementing locally appropriate regulations, including those related to zoning, storm water management, and building codes, and attending to the needs of vulnerable populations through measures such as basic service provision and the promotion of equitable policies and plans. Among the important institutions are those associated with local governments as they have a major role in translating goals, policies, actions, and investments between higher levels of international and national government to the many institutions associated with local communities, civil society organizations, and nongovernment organizations (NGOs).

Mimura et al. (2014) noted that national governments assume a coordinating role of adaptation actions in subnational and local levels of government, including the provision of information and policy, creating legislation, acting to protect vulnerable groups, and, in some cases, providing financial support. Undertaking adaptation at the local level, local agencies and planners are often confronted by the complexity of adaptation without adequate access to guiding information or data on local vulnerabilities and potential impacts. Even when information is available, they are left with a portfolio of options to prepare for future climatic changes and the potential unanticipated consequences of their decisions. Therefore, linkages with national and subnational levels of government, as well as the collaboration and participation of a broad range of stakeholders, are important.

Existing and emerging economic instruments (risk sharing and transfer mechanisms, loans, public-private finance partnerships, payments for environmental services, improved resource pricing, charges and subsidies, including taxes, norms, and regulations) can foster adaptation by providing incentives for anticipating and reducing impacts. Risk financing contributes to increasing resilience to climate extremes and climate variability but can also provide disincentives, cause market failure, and decrease equity. Mechanisms include insurance and national, regional, and global risk pools, while the public sector often plays a key role as regulator, provider, or insurer of last resort (Field et al. 2014).

Available strategies and actions can increase resilience across a range of possible future climates while helping to improve human livelihoods, social and economic well-being, and environmental quality. Integration of adaptation into planning and decision making can promote synergies with sustainable development and reduce the possibility of maladaptive actions. Adaptation can generate larger benefits when connected with development activities and disaster risk reduction. Adaptation strategies that also strengthen livelihoods, enhance development, and reduce poverty include improved social protection, improved water and land governance, enhanced water storage and services, greater involvement in planning, and improved attention to urban and peri-urban areas affected by migration of poor people (Field et al. 2014).

Indigenous, local, and traditional forms of knowledge are an important resource for adapting to climate change. But the emerging climate change impacts are beyond the range of expertise, hence such traditional knowledge will be challenged. Such forms of knowledge are often neglected in policy and research, and their recognition and integration with scientific knowledge will increase the effectiveness of adaptation.

Global adaptation cost estimates are substantially greater than current adaptation funding and investment, particularly in developing countries, suggesting a funding gap and a growing adaptation deficit.

3.3 Adaptation in Selected Sectors

Noble et al. (2014) distinguished categories and examples of adaptation options, including structural/physical (engineered and built environment, technological ecosystem based, services), social (educational, informational, behavioral), and institutional (economic laws and regulations, government policies, and programs). They also list a plethora of examples of adaptation options referring to various sectors, falling into these categories. Well-studied examples are reported in Field et al. (2014).

Adaptation in such sectors as agriculture, forestry, and industry has impacts on the freshwater system and, therefore, needs to be considered jointly while planning adaptation in the water sector (Jiménez et al. 2014). For example, better agricultural land management can also reduce erosion and sedimentation in river channels, while controlled flooding of agricultural land can alleviate the impacts of urban flooding. Increased irrigation upstream may limit water availability downstream. A project designed for other purposes may also deliver increased resilience to climate change as a co-benefit, even without a specifically identified adaptive component.

Vulnerability can be reduced by management measures that help improve human health, livelihoods, social and economic well-being, and environmental quality.

Freshwater resource management is clearly linked to other policy areas (e.g., sustainable development, energy, nature conservation, disaster risk prevention). Hence there is an opportunity to align adaptation measures across several water-dependent sectors. Adaptation to climate change should also include reduction of the many non-climate-related pressures on freshwater resources, such as water pollution and increase of water withdrawals, as well as improvement of water supply and sanitation. These win-win or even multiple-win (no regret) measures, providing co-benefits, would reduce the vulnerability to climate change and would be beneficial even if future climate change impacts on freshwater resources at the local scale cannot be precisely known.

Some areas will require long-lasting and costly efforts of redesigning and building higher levees and larger storage volumes to accommodate larger future flood waves if the same (or higher) safety standards have to be reached. Water quality systems may need to be designed to cope with lower self-purification in warmer water, and increased turbidity and pollution may increase significantly the costs and challenges of treating water to potable standards. The stake is high, as annual global investments in water infrastructure can easily reach hundreds of billions of US$.

Water management measures that increase resilience across a range of possible future climates go beyond structural measures and include rainwater harvesting, conservation tillage, maintaining vegetation cover, planting trees on steep slopes, mini-terracing for soil and moisture conservation, improved pasture management, water reuse, desalination, protection and restoration of freshwater habitats and of the water retention capacity of floodplain as well as improved soil and irrigation management. Typically, “soft” institutional measures are combined with “hard” infrastructural measures. Measures have to be tailored to local socioeconomic and hydrological conditions. Forecasting-warning systems, e.g., for floods and droughts, insurance instruments, and a plethora of means to improve the efficiency of water use (e.g., via demand management) can reduce adverse climate change impacts. Also important are behavioral changes, economic and fiscal instruments, legislation, and institutional changes.

Climate change is only one of the several interacting stressors of freshwater systems, all of which have to be managed well. Reduction of risks caused by non-climatic drivers like human water demand and pollutant emissions will often reduce climate-related risks, as vulnerability to climate change is decreased. In this way, managing the risks of climate change may at the same time contribute to reducing risks caused by non-climatic drivers.

Agriculture is a critically water-dependent sector, the more so the greater world population and attendant global food demand. If, for example, climate change brings about decreases in crop yields (mediated by decreasing water availability), specific adaptation measures need to be put in place. This portfolio ranges from more effective water use in irrigation—noting that irrigation efficiency is worryingly low in many places—more effective water use in rain-fed agriculture, including water harvesting and soil conservation methods, and eventually changes in diets, in concert with a paradigm shift away from a focus on freshwater supply toward demand management. There is no blueprint solution for tackling water scarcity in food production; site-specific combinations of adaptive measures are needed that optimally account for the water-food-energy nexus in multipurpose systems, ensuring resource use efficiency in these three domains alike (Hoff 2011). Regions without enough water to produce desired goods may benefit from international trade–indeed, virtual water trade is an effective adaptation measure in an increasingly connected world, which may play an even more prominent role in the future.

Less irrigation water might be required for paddy rice cultivation in monsoon regions where rainfall is projected to increase and the crop growth period to become shorter. Water demand for rain-fed crops could be reduced by better management, but unmitigated climate change may counteract such efforts, as shown in one global modeling study. In some regions, expansion of irrigated areas or increases of irrigation efficiencies may overcome climate change impacts on agricultural water demand and use. Land management practices (e.g., conservation tillage) are critical for mitigating soil erosion under projected climate change.

Urban adaptation has emphasized city-based disaster risk management such as early warning systems and infrastructure investments, ecosystem-based adaptation and green roofs, enhanced storm and wastewater management, urban and peri-urban agriculture improving food security, enhanced social protection, and good quality, affordable, and well-located housing (IPCC 2014).

There is a complex interplay between adaptation to, and mitigation of, climate change. In general, mitigation policies reduce the impacts and need for adaptation to climate change but some mitigation measures (e.g., bioenergy) may constrain adaptation options and even consume freshwater resources that could alternatively be used for crop irrigation or other purposes. Afforestation to sequester carbon has important co-benefits of reducing soil erosion and providing additional habitat, but may reduce renewable water resources.

Linkages among water, energy, food/feed/fiber, and climate are strongly related to land use and management, which can affect water as well as other ecosystem services, climate, and water cycles (Field et al. 2014). Many energy sources require significant amounts of water, either directly (e.g., crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations), and produce a large quantity of wastewater that requires energy for treatment. Some potential water management adaptation measures (e.g., pumping of deep groundwater or water treatment) are very energy intensive. Some nonconventional water sources (wastewater or seawater) are highly energy intensive but costs of desalination are progressively decreasing.

Noble et al. (2014) framed the notion of maladaptations as those that may benefit a particular group, or sector, at a particular time but may prove to be maladaptive to those same groups or sectors in future climates or to other groups or sectors in existing climates. Some development policies and measures that deliver short-term benefits or economic gains may lead to greater vulnerability in the medium to long term. For example, construction of "hard" infrastructure reduces the flexibility and the range of future adaptation options. Noble et al. (2014) listed the principal problems related to maladaptation options that can: (1) increase emissions of GHGs, (2) disproportionately burden the most vulnerable, (3) have high opportunity costs, (4) reduce incentives and capacity to adapt, and (5) set paths that limit future choices.

3.4 Governance of Climate Change Adaptation and Disaster Risk Reduction

Governance of climate change adaptation and disaster risk reduction denotes exercise of political, administrative, and economic authority. It comprises the mechanisms, processes, and institutions through which citizens and groups articulate their interests, exercise their legal rights, meet their obligations, and mediate their differences (Green and Kundzewicz 2015). Governance should resolve controversies and conflicts of interest of stakeholders.

The governance has to provide a useful and appropriate means of intervention and to be successful in addressing the nature of choices and collective decision making and result in an effective means of implementing those decisions (Green and Eslamian 2014). Governance (what is decided and how it is implemented) is done by people interacting with each other; it is social relationship in practice.

The question can be posed: how does governance deliver? The formal structure can be seen as a multidimensional figure of actors and such constructs as power and resources, the capacity to induce or resist change, discourses, and rules. Discourses, held by actors, are purposive and normative: they are interpretations, intended to guide action, but the actors holding an interpretation also seek for the other actors to hold the same interpretation (coalition building). Discourses may also include interpretation about social relationships and the relationships between people and the environment. So discourses are rule forming and power creating. Any intervention option requires an appropriate arrangement of actors with the powers to adopt or implement the option successfully (Green and Kundzewicz 2015).

To better support decision making in the context of climate change, a new focus on risks has been adopted in the IPCC process (Field et al. 2012, 2014). Risk can be understood as the potential for negative consequences where something of value is at stake and where the outcome is uncertain. The risk that a certain impact (adverse consequence for a natural or human system) of climate change occurs results from the interaction of hazard (potentially occurring physical events as affected by climate change), exposure (presence of people, ecosystems, and assets in places and settings that could be adversely affected by a hazard), and vulnerability (predisposition to be adversely affected). Risk is often estimated as the probability of occurrence of hazardous events multiplied by the impacts that ensue if these events do occur (IPCC 2014).

Table 2.1 Flood risk reduction strategies

I. Keeping water away from people
Flood defense
Flood flow improvement and retention
II. Keeping people and wealth away from water
Flood risk prevention
III. Being prepared to a flood occurrence
Flood risk mitigation
Flood preparation
Flood recovery

Risks associated with climate change are not caused by anthropogenic climate change alone but also by climate variability and by socioeconomic conditions and processes. Climate change is not the only risk; nonetheless, it is a significant risk.

3.4.1 An Example of Risk Management: Flood Risk Reduction Strategies and Governance Arrangements

Flood risk reduction strategies need to consider jointly the landscape changes that affect flood response, the location and protection of people and property at risk, as well as changes in flood risk due to changes in climate. All three are of critical importance to the future flood hazard and economic losses due to flooding (Kundzewicz et al. 2014). The roster of strategies is illustrated in Table 2.1.

At times, we lose focus on the things we already know for certain about floods and how to mitigate and adapt to them. A simple blaming of climate change for increase in flood losses is not scientifically sound and can be counterproductive as it makes flood losses a global issue that appears to be out of control for regional or national institutions.

Current studies indicate that increasing exposure of population and assets, rather than anthropogenic climate change, is primarily responsible for the mounting increase in flood losses. While early warning systems can successfully reduce mortality risk through evacuation of the population, crops and infrastructure remain in place, and hence the significant increase in infrastructure has led to a drastic increase in economic risk. Studies that project future flood losses and casualties indicate that, when no adaptation is undertaken, future anthropogenic climate change and the increase in exposure linked to ongoing economic development are likely to lead to increasing flood losses. Where rapid urbanization brings inadequately engineered in-city drainage infrastructure as well, its effect can promote rather than decrease losses to both the economy and human lives (Kundzewicz et al. 2014).

European Union Floods Directive

In response to several destructive floods in Europe since the 1990s, the European Union (EU) Floods Directive (CEC 2007) was adopted. The directive obliges EU Member States to undertake, for each river basin district or each portion of an international river basin district or coastal area lying within their territory:

- A preliminary flood risk assessment (a map of the river basin; description of past floods; description of flooding processes and their sensitivity to change; description of development plans; assessment of the likelihood of future floods based on hydrological data, types of floods and the projected impact of climate change and land use trends; forecast of estimated consequences of future floods)
- Preparation of flood maps and indicative flood damage maps, for areas which could be flooded with a high probability, with a medium probability, and with a low probability (extreme events)
- Preparation and implementation of flood risk management plans, aimed at achieving the required levels of protection

Since the EU Floods Directive is closely related to implementation of the EU Water Framework Directive, plans for implementations of these both directives are fully synchronized, and close coordination of processes of implementation of directives and of social consultation is strived for, in the expectation of achieving complementary objectives.

The subsidiarity principle, guiding the EU policy, means that Member States may react flexibly to the specific challenges in their countries. Adaptation is basically local. However, the EU plays a coordination role when dealing with transboundary issues and sectoral policies. It provides co-funding of a range of projects (including infrastructure). The EU supports research, information exchange, awareness raising, and education. In brief, it attempts to create an enhancing environment.

3.5 Limits and Barriers to Adaptation

Limits to adaptation to climate change of water and land resources may manifest themselves as the inability to prevent intolerable risks to objectives and/or needs of a system. Limits to adaptation can be categorized as (cf. Kundzewicz et al. 2007, 2008, Jimenez et al. 2014):

1. Physical limits (it may not be physically possible to prevent adverse effects)
2. Economic limits (even if it is physically feasible to adapt, there are economic constraints to what is affordable)
3. Political and social limits (e.g., relocation of people or constructing reservoirs may not be socially and politically acceptable while reduced reliability or standard of service may be unpalatable)

4. Institutional limits (e.g., inadequate capacity of water management agencies—existing arrangement of actors, rules, and constraints on how power may be exercised)

Common constraints on implementation arise from such factors as uncertainty about projected impacts, limited financial and human resources, limited integration or coordination of different levels of governance, different perceptions of risks, inadequate responses from institutions, and limited tools to monitor adaptation effectiveness. Underestimating the complexity of adaptation as a social process can create unrealistic expectations (Field et al. 2014).

In cases where the limits to adaptation have been surpassed, losses and damage may increase and the objectives of some actors may no longer be achievable. While limits imply that intolerable risks and damages can no longer be avoided, there can be both "soft" and "hard" limits to adaptation. In the case of the former, there are opportunities in the future to alter limits and reduce risks, for example, through the emergence of new technologies or changes in laws, institutions, or values, while in case of the latter, there are no reasonable prospects for avoiding intolerable risks.

There may be a need for transformational adaptation to change fundamental attributes of a human system in response to actual or expected impacts of climate change, i.e., not only for adapting to the impacts of climate change but for redefining objectives and rendering them more attainable, altering the systems and structures, economic and social relations, and behaviors that contribute to climate change and social vulnerability. It may involve adaptations at a greater scale or intensity than previously experienced, adaptations that are new to a region or system, or adaptations that transform places or lead to a shift in the location of activities.

Limits to adaptation are context specific and closely linked to cultural norms and societal values (Field et al. 2014). Understanding of limits to adaptation can be informed by historical experiences, or by anticipation of impacts, vulnerability, and adaptation associated with different scenarios of climate change. For example, barriers to adaptation to floods via relocation (resettlement) can be external, e.g., lack of land for relocation, or internal, such as unwillingness of people to relocate. The greater the magnitude of climate change, the greater the likelihood that adaptation will encounter limits.

4 Conclusions

Notwithstanding the urgent need for climate change mitigation, it is absolutely crucial to adapt to climate change and its impacts. Risks of climate change impacts on water and land have affected natural and human systems and are projected to increase significantly with increasing greenhouse gas concentrations. There are a range of key risks, spanning sectors, and regions.

Climate change will affect current water management practices and the operation of existing water infrastructure.

There are two approaches to choosing between alternative courses of action in the situation of strong and possibly irreducible uncertainty – there are the precautionary principle and adaptive management.

Responding to climate-related risks involves decision making in a changing world, with continuing uncertainty about the severity and timing of climate change impacts and with limits to adaptation. Adaptation and mitigation choices in the near-term involve decisions with implications for future societies, economies, environment, and climate and will affect the risks of climate change over long time.

We can influence the risk related to adverse anthropogenic climate change impacts by adaptation to climate change (treating symptoms of a problem) or by mitigation of climate change (an indirect option with high inertia—treating sources of a problem) and its adverse impacts. Prospects for climate-resilient pathways for sustainable development are related fundamentally to what the world accomplishes with climate change mitigation. Greater rates and magnitude of climate change increase the likelihood of exceeding adaptation limits—for a strong climate change, satisfactory adaptation would be much costlier and difficult, if not impossible.

Significant co-benefits, synergies, and tradeoffs exist between mitigation and adaptation and among different adaptation responses. Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, particularly at the intersections among water, energy, land use, and biodiversity, hence in the context of section S3. Examples of actions with co-benefits include improved energy efficiency and cleaner energy sources, leading to reduced emissions of health-damaging climate-altering air pollutants, reduced energy and water consumption in urban areas through greening cities and recycling water, sustainable agriculture and forestry, and protection of ecosystems for carbon storage and other ecosystem services.

Since the impacts of climate change and the most effective way of adapting to change depend very much on local geographic, economic, social, and political conditions, it is difficult to extrapolate results or conclusions. Climate change is superimposed onto other pressures on resources.

A first step toward adaptation to future climate change is reducing vulnerability and exposure to present climate variability. Strategies include actions with co-benefits for other objectives. Adaptation planning and implementation are contingent on societal values, objectives, and risk perceptions.

Acknowledgments The author acknowledges the useful and constructive remarks of two anonymous referees that helped improve this document.

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Chapter 3
Climate Change, Profligacy, Poverty and Destruction: All Things Are Connected

Brian Moss

Abstract Climate change is linked with profligacy in richer societies, poverty in the developing world and destruction of natural ecosystems everywhere. Adaptation to climate change is essential because the effects are already with us, but it is a short-term manoeuvre that pretends the problem can be tolerated indefinitely and fails to recognise the linked problems. Mitigation through the curbing of carbon emissions is essential but is proving very difficult. Temperatures will not stabilise until carbon sinks annually match carbon emissions. Our problems are global and so, therefore, must be our ultimate governance. Much needs to be done to achieve such governance but time is short. Three immediate steps are possible: agreement to begin curbing carbon emissions substantially but also to increase greatly the extent of natural carbon-storing ecosystems through contraction of agriculture and reform of food production and distribution systems to favour healthier diets; replacement of GDP by an index that accounts for the natural and human costs of exploitative economic activity and discourages environmental damage; and corresponding reform of taxation systems to recover the true costs of that damage. These three steps could begin a more optimistic path for the future.

1 Introduction

> *We would rather be ruined than changed. We would rather die in our dread than climb the cross of the moment and let our illusions die.* W. H. Auden. Epilogue. The Age of Anxiety 1947

> *The problems of the world cannot possibly be solved by sceptics or cynics whose horizons are limited by the obvious realities. We need men [and women] who can dream of things that never were.* John F. Kennedy, Dublin June 28 1963

> *Our economists are exposed by climatologists as utopian fantasists, the leaders of a millenarian cult as mad as, and far more dangerous than, any religious fundamentalism. But their theories govern our lives, so those who insist that physics and biology still apply are*

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H. Hettiarachchi, R. Ardakanian (eds.), *Environmental Resource Management and the Nexus Approach*, DOI 10.1007/978-3-319-28593-1_3

Fig. 3.1 Chief Seathl (*left*) and Mrs Gro Harlem Brundtland (*right*)

> *ridiculed by a global consensus founded on wishful thinking.* George Monbiot, The Guardian, 15 February 2005

All things are connected, the native American chief Seathl (Fig. 3.1) is reported to have said in 1854. He was referring to the relationship of his Suquamish people to the land in the northwestern USA that government agents were attempting to wrest from them. The speech was made in a dialect of Salish. Dr Henry Smith, a local settler, made notes at the time and worked them up for an article published by the Seattle Sunday Star in 1889, thirty-five years later. Smith was not fluent in Salish and there are now several, even more derivative, versions of the speech. Ted Perry wrote the most famous as a film script in 1971 (Suzuki and Knudtson 1994). It is powerful writing and, whatever the provenance, a pithy comment on the problems we now face and the underlying philosophy of the nexus approach. Climate change is not a single problem; it is part of a network rooted in human nature (Fig. 3.2). Any proper solution to the climate change problem must rest in the mutual solution of these other problems.

Around a century after Seathl's speech, Mrs Gro Harlem Brundtland (Fig. 3.1), former prime minister of Norway, led a United Nations Commission that resulted in a report called *Our Common Future* (World Commission on Environment and Development 1987). The Commission was a respected, establishment-based group of senior politicians and advisors but notably with only two environmental scientists among 23 members, but it took evidence from a wider range of people. It concluded that the world had serious problems, not least a major division between a poor majority in developing countries and a very rich minority in the developed ones,

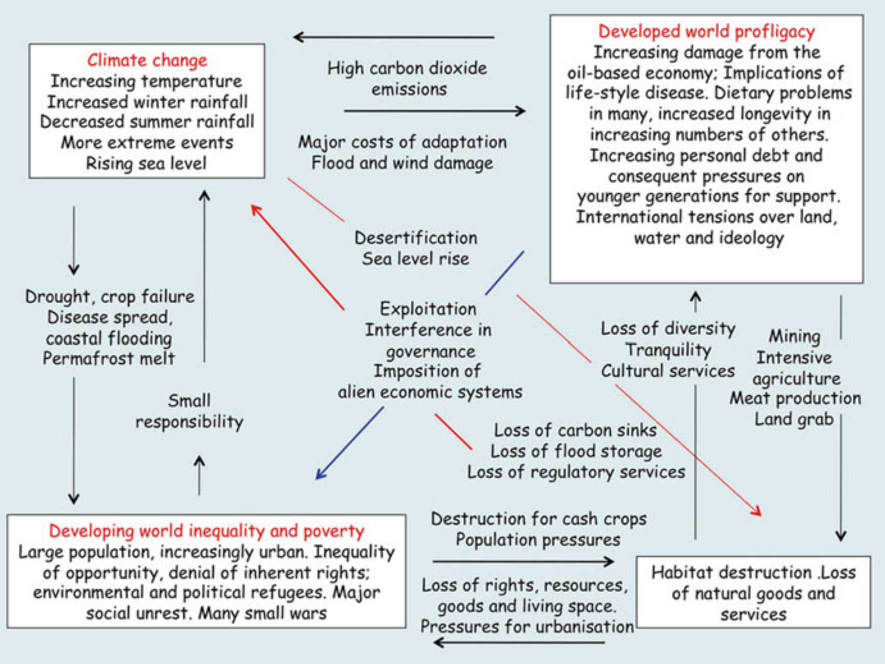


Fig. 3.2 The ultimate nexus: four groups of global problems and their linkages

linked with increasing damage to land, air, water and ecosystems. It proposed that the solution was ‘sustainable development’, defined as meeting the needs of the present without compromising the ability of future generations to meet theirs, and it proposed that equal consideration for environment, economic and social factors would be necessary in finding solutions. It was a real advance.

1.1 Our Common Future

The Report did many good things. It brokered three United Nations institutions that have produced significant reports of their own: the Millennium Development Commission, the Millennium Ecosystem Assessment and the Intergovernmental Panel on Climate Change. The Millennium Development Commission reported in 2006 and set eight goals: to eradicate extreme poverty and hunger; to achieve universal primary education; to promote equality and to empower women; to reduce child mortality; to improve maternal health; to combat HIV/AIDS, malaria and other diseases; to ensure environmental sustainability; and to promote a global partnership for development. The goals had defined targets and it was recognised that the seventh goal, on environmental sustainability, was basic to the others. A date for achievement was set as 2015. The UN has regularly monitored progress towards the goals and some targets are likely to be met, though no goal in entirety (United Nations 2014). The targets for environmental sustainability largely concern sanitation, drinking water and general living conditions in slums. Two, reversing the loss of forests and global emissions of carbon dioxide, have wide implications and are the targets least likely to be achieved. In 2015, the goals will be renewed as Sustainable Development Goals (Stafford Smith 2014).

The prime thrust of the Millennium Development Goals was in the social and economic interests of the Brundtland triplet. Two further bodies have considered the environmental issues. The Millennium Ecosystem Assessment, reporting in 2004, found that around 50 % of natural forests, grasslands, freshwaters and other world ecosystems had been seriously damaged by 1950 and that on present trends, this value would rise to 70 % by 2050. The damage comes immediately from deforestation and desertification and ultimately from the impact of human numbers, climate change, introduction of alien species, nutrient pollution from effluents, agricultural run-off and vehicle exhaust and overharvesting, especially of fish.

The assessment established the idea that natural systems provide goods and services to people, for example, timber, food, water and grazing, which can be given a cash value and included in economic analyses of costs and benefits. It also noted spiritual and cultural values, some of which, the value to the tourist industry of game reserves and scenic areas, for example, can also be given a cash value, others of which cannot. There is no value of any meaning that can be given to the inspiration that the English Lake District gave to William Wordsworth's poetry or of the western American mountains to the photographs of Ansel Adams. Ecosystem services also include regulatory services, the processes that maintain the composition of the atmosphere, waters and soils, on which the entire living system of the Earth, including ourselves, absolutely depends (Lenton and Watson 2011; Tyrrell 2013). Some of these, the protection given by salt marshes and mangrove swamps during storms to the hinterland of human habitation behind them, for example, can be given a cash value in terms of damage prevented, but the greater global services cannot (Fitter 2013) for they are irreplaceable and what is irreplaceable is priceless. Nonetheless attempts have been made to place notional values on these things. Environmental economists have shown that intact ecosystems are far more valuable to humanity as a whole than developed systems (Costanza et al. 1997, 2014; Balmford et al. 2002) and that the value of what is now called natural capital is annually vastly greater than that of the agricultural and manufacturing economies.

Among the forces that damage natural systems, climate change has come to prominence with the findings of the third United Nations body, the Intergovernmental Panel on Climate Change, in its five increasingly concerned reports, the latest of which was published in 2013/14. Release of greenhouse gases, notably carbon dioxide from the burning of fossil fuels, cement manufacture and the destruction of forests, has already resulted in a net average warming of the world by 0.7 °C, but by 2.5 °C in the Arctic where the summer sea ice cover has melted to an unprecedented extent compared with the last few hundred thousand years. There are increases in other gases that are more powerful in absorbing heat radiation, including methane from intensive rice cultivation and cattle husbandry, nitrous oxide from nitrogen fertilisation and vehicle engines, man-made chlorofluorocarbons and hydrochlorofluorocarbons, used as refrigerants, and ozone produced from oxygen at ground level by the action of sunlight on petrol fumes.

Climate models show that a several-degree rise in temperature is likely during this century, but temperature rise is only one symptom. Sea levels have risen by 20 cm from expansion of the water of the ocean and glacier melting (IPCC 2014); there is greater winter rainfall or more intense summer droughts in many areas, and an increase in frequency of extreme weather events as the atmosphere redistributes an increased amount of energy (IPCC 2014). Repeated major meetings among world governments have failed to reach agreement on the necessary cuts in carbon dioxide emissions necessary to avert a more than 2 °C warming, and there are doubts that serious problems will be avoided by such a limit. The most recent document of the United Nations Framework Convention (UNFC) Conference of the Parties 21 (2015) written in Paris is a step forward, but is considered to be weak. Emphasis has thus been placed to a greater extent on adaptation to present and immediately anticipated changes. Adaptation will, however, be a spontaneous response of local communities, and the setting up of high-level committees by national governments to give advice appears often to result in statements of the obvious (H.M. Government 2013; Committee on Climate Change (UK) 2013). If it leads to policy changes on land management, for example, concerning flood control and water storage, adaptation will be a useful concept, and assuredly it will have a needed positive effect in reducing immediate impacts. But it is alone not sufficient and may also be a diversion from the real business of mitigation. Adaptation is merely response to symptoms. Mitigation of cause is needed, and hitherto, failure to agree on substantial cuts in emissions has led to reconsideration of large and possibly dangerous engineering fixes to reduce the temperature.

1.2 A Crucial Mistake

For all the immense value of the Brundtland Report, I believe it made a crucial mistake. Environmental, social and economic factors are not of equivalent importance. There is a hierarchy. It is the position of this paper that mitigation of climate change rests fundamentally on primary understanding of the natural science of our species and of our planet, with socio-economic issues entering the arena secondarily. It is possible to adapt initially to the symptoms using social and economic instruments but eventually these symptoms are likely to become too severe. Permanent solutions must come from understanding of ultimate causes and not from cosmetic treatment of their symptoms. If the natural environmental issues and the biological nature of humanity are not accommodated first, the social and economic issues become irrelevant. There may not be an organised human society to worry about. Like it or not, we are an evolved biological species, with basic requirements similar to all other species that prescribe limits that we cannot ignore or override.

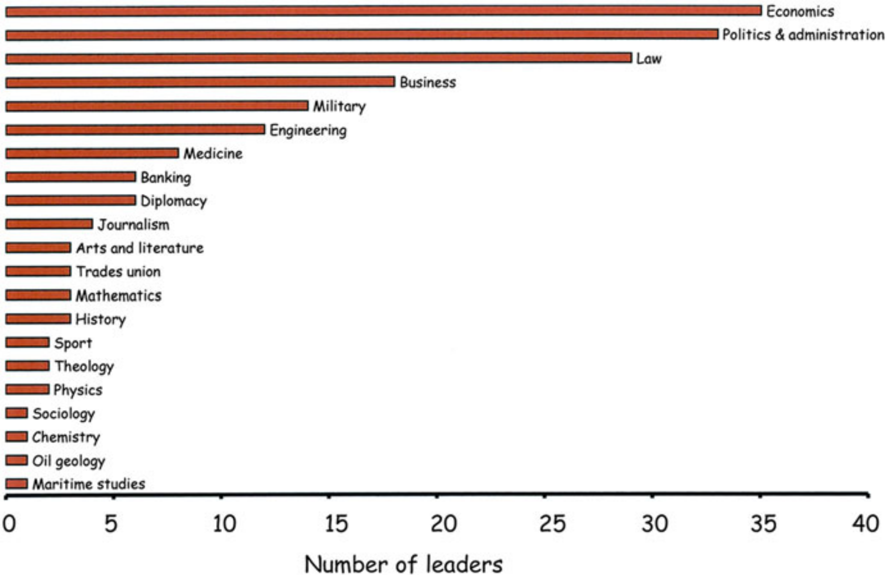


Fig. 3.3 Backgrounds of the 194 national leaders (From Moss 2012)

My approach is first to recount the history of change on Earth and the evolution of humans, to explain how our present predicament arises because of our biological nature, including the high brain capacity that makes possible our culture. It then moves on to describe how the problems we have created, including those of climate change, increased urbanisation and burgeoning population, are linked and ultimately one problem (Subtheme 1 of this conference). It concentrates on restoration of natural biomes as carbon stores as an essential step in solution (Subthemes 1 and 2). Thirdly it illustrates how analogies with ecosystems can help in the restructuring of socio-economic systems to solve the problem and suggests how understanding of the issues can point to a strategy of governance (Subtheme 2 of this conference) that might give solutions that are equitable among all peoples. The strategy cannot preserve all existing privileges and it cannot embrace indefinite economic resource-based growth, for that is a delusion, but it can lead to a reasonably comfortable future.

It is a strategy resting fundamentally in natural science that must use economics, law and the humanities to bring to fruition, but understanding of the natural science has to be the prime basis. The former British prime minister, Winston Churchill, once said that scientists should be ‘on tap but not on top’ (Churchill 1965). Most scientists would not want to be on top, but the tap needs to be left running. Current discussions often leave it only dripping or firmly turned off. Of the leaders of the 194 countries of the world, investigated in 2011, only one had any sort of qualification in environmental sciences (a master’s diploma in maritime studies). Seventy-five per cent came from economics, politics, business and finance, law and the military (Fig. 3.3). We face our most important global problems seriously handicapped by biased governance.

2 Climate and Our Place in Nature

2.1 Earth and Life Have Intertwined Histories

Earth has a long history of change, culminating in conditions at the surface now controlled by living organisms (Lenton and Watson 2011; Moss 2012). For the past few hundred million years, these conditions have been within the range in which large, complex organisms, like us, can survive. Before that, and for most of Earth's history of around 5 billion years, its environment was suitable only for microorganisms, initially anaerobic bacteria, which are poisoned by free oxygen. A big change began about 2.5 billion years ago, when, in the world's oceans, bacteria (Fig. 3.4) evolved the ability to use water molecules to fix carbon dioxide into organic matter, using the energy of sunlight, a process known as oxygenic photosynthesis. The snag was that very poisonous molecular oxygen was released as a by-product. The first tranches of oxygen were mopped up by inorganic chemical mechanisms, but eventually these became exhausted, and by 1.5 billion years ago, the oxygen levels in the atmosphere had increased to problematic levels for most of the cells that had hitherto been the only inhabitants of Earth.

This caused something of a crisis, solved by evolution of a new sort of cell (Fig. 3.4) from a nesting, or symbiosis, of several smaller cells, like Russian dolls, in a larger host cell. This buried the oxygen-sensitive systems deep in the host cell, where oxygen levels could be controlled. Evolution is resourceful and oxygen gave the possibility of releasing much more energy from the photosynthetic products, and the elaboration of bigger, more complex organisms made up of many cells that formed specialised tissues. Around 600 million years ago, this process was well under way, and oxygen concentrations were increasing well above 1 %, whilst carbon dioxide levels had been reduced, by incorporation of the carbon into biomass and stores in the rocks (ultimately to become coal, natural methane gas, oil, chalk and limestone) to much less.

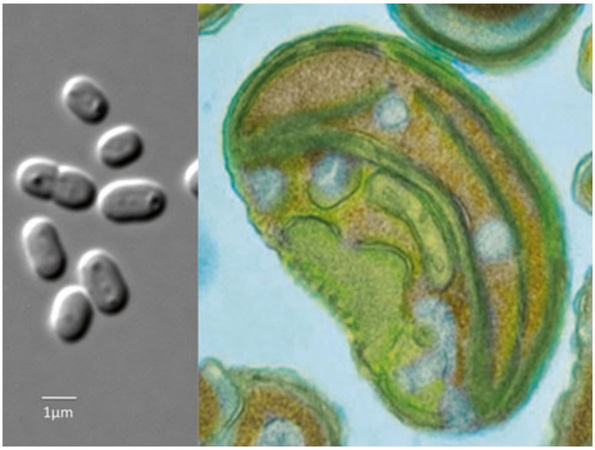


Fig. 3.4 A marine cyanobacterium (*left*) and a more complex cell (*Ostreococcus*) derived by symbiosis from bacterial cells following the rise in oxygen concentrations about 1.5 billion years ago. The membranes bearing chlorophyll, which catalyses oxygenic photosynthesis, can be seen

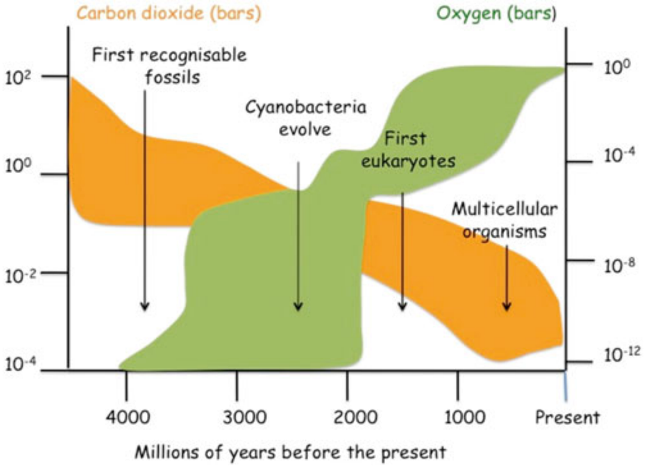


Fig. 3.5 Changes in oxygen and carbon dioxide concentrations in the Earth's atmosphere over the lifetime of Earth. The depth of the coloured areas indicates the uncertainties in the estimates. Note that the vertical scale is logarithmic (Based on Mojzsis 2001)

Over the last 600 million years, evolution has elaborated a succession of different ecosystems on land and in the ocean, with different groups dominating at successive times (the amphibians and lichens after the first colonisation of the land, the dinosaurs and trees of the fern family later and now the flowering plants, insects, mammals and birds), but at each stage, the basic characteristics of ecosystems have remained broadly the same. Energy is fixed by plant photosynthesis (algal photosynthesis in the oceans) and passed through food webs of grazers, detritus feeders on dead organic matter and predators, with residual organic matter and carcasses being decomposed by microorganisms that release the 20 or so essential, and often scarce, chemical elements for reuse. There are global cycles of all the elements, and of water, which acts as a medium in which elements can be transferred. The cycle of carbon is of particular interest for there is a small surplus of photosynthesis over respiration, the process that releases energy and regenerates carbon dioxide. This means that there is a continual small surplus of oxygen generated and some carbon is bound into organic deposits in peats, soils and lake and ocean sediments. Carbon dioxide tends thus to be kept down in concentration and oxygen up. Major deviations in either would be problematic. Too much oxygen would mean that natural lightning-caused fires would burn extensively, even in wet vegetation; too little carbon dioxide would mean that the Earth would cool rapidly and too much that it would heat up. The excess of oxygen is mopped up by trace gases like methane that are produced by living organisms in wet soils and in the guts of termites and ungulate mammals, whilst carbon dioxide is replaced by volcanic eruption (see Lenton and Watson 2011 and Moss 2012, for more details).

Over the past 600 million years, the concentrations of oxygen and carbon dioxide have been maintained within narrow ranges (Fig. 3.5) that permit equable temperatures and avoid major conflagration and severe cooling, but there have been

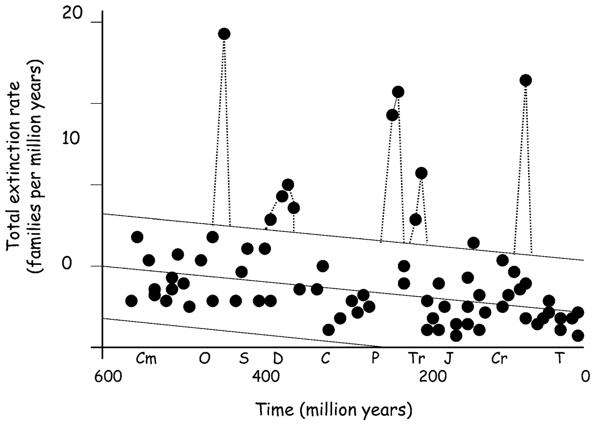


Fig. 3.6 Extinction rates of families of organism, derived from the fossil record, during the past 600 million years. The peaks are caused by unusual events. The parallel lines indicate the background trend (From Moss 2012)

extremes. There was a recent glaciation during a complex series of events involving the natural variations of orbit of the Earth, which take it a little further away from the Sun from time to time. At the other extreme, in the Carboniferous period, increased production led to large burials of carbon (which eventually formed coal). The progress of erosion of mountain masses on what was then a huge continent, Pangaea, centred on the Equator, had produced a large flat, swampy land where huge forests had built up and oxygen levels had risen. Forest fires broke out that were so extensive their ash fertilised the oceans, increasing production there, deoxygenating the water and causing a major extinction of marine animals. Later, in the Jurassic, collision of the Earth with a large asteroid caused upheaval and extinction.

But despite a geological past of sometimes violent disruption, as well as the irregular movements of drifting continents and regular shifts in the shape of the Earth's orbit around the Sun, the biosphere has been resilient. Evolution and the versatility of life have repaired the damage, and changes have been accommodated. There is even some evidence that background conditions (outside the unpredictability of events like asteroid collision) have become steadier because background extinction rates, judged from changes in the fossil assemblages, seem to have steadily decreased (Fig. 3.6).

2.2 *Natural Selection*

The process of accommodation to a changing environment is well understood. The principles are fundamental to biology through the mechanism of natural selection. All organisms are controlled by information held in their collection of genes, which are made of nucleic acid, DNA, and passed from generation to generation almost intact, but not quite. Sexual mechanisms produce new combinations of genes from the two parents, and small chemical alterations driven by ultraviolet light, or other radiation, mutate the nature of individual genes. Every new generation of every organism consequently harbours a great deal of variation. Some individuals will survive more readily in the circumstances of the time. They will avoid perils, obtain food more easily, attract mates more effectively and produce more surviving offspring. Their gene combinations will have been passively selected and the same process will go on in every generation. Natural selection tempers the adaptation of every species through inevitable success in reproduction of the better-fitted individuals. It also selects mechanisms for maintenance of variability so that there is always raw material to cope with new challenges. Genetic diversity is an insurance policy against future change.

There is also a tendency in this evolutionary process for mechanisms to develop that give increasing self-preservation. The first such major example was the ability to use the copiously abundant water in photosynthesis, compared with the scarce hydrogen sulphide that had been used previously; the next was the development of complex cells that could cope with free oxygen produced by this process. Then there was the development of organisms with many cells where there could be specialisation of the tissues for different functions. Later, the evolution of water-resistant covers and bony or woody support could allow colonisation of the land and exploitation of the greater amounts of light available there, despite the dryness. There is a metaphor of the environmental theatre and the evolutionary play (Hutchinson 1965). The theatre continually changes, but the players are replaced or adapt their roles; the play is kept going and the plot remains one of survival, but it has become a more sophisticated plot with time. And its latest twist has been very significant.

2.3 Human Evolution

Human evolution is the latest and very recent stage, with the first hominids appearing around 3 million years ago. Our present species emerged in Africa from a group of similar species of *Homo* only 100,000 years ago and, showing every characteristic of a vigorously invasive species, has spread over the continents. The key characteristic of this line has been the size of the brain. We share other characteristics with other organisms, to complete extents where basic needs of food and energy, gene production and action are concerned and many to large extents where the details of self-preservation and acquiring mates are concerned. Our brain size (or specifically the size of the cerebral hemispheres), however, has increased steadily over 3 million years of our recent evolution (Fig. 3.7) and now gives us a great advantage compared even with our fellow great apes. It allows us to reason and understand mechanisms to a hugely greater extent. It has liberated us partly from natural selection in that instead of reacting to changes in our environment, we can modify that

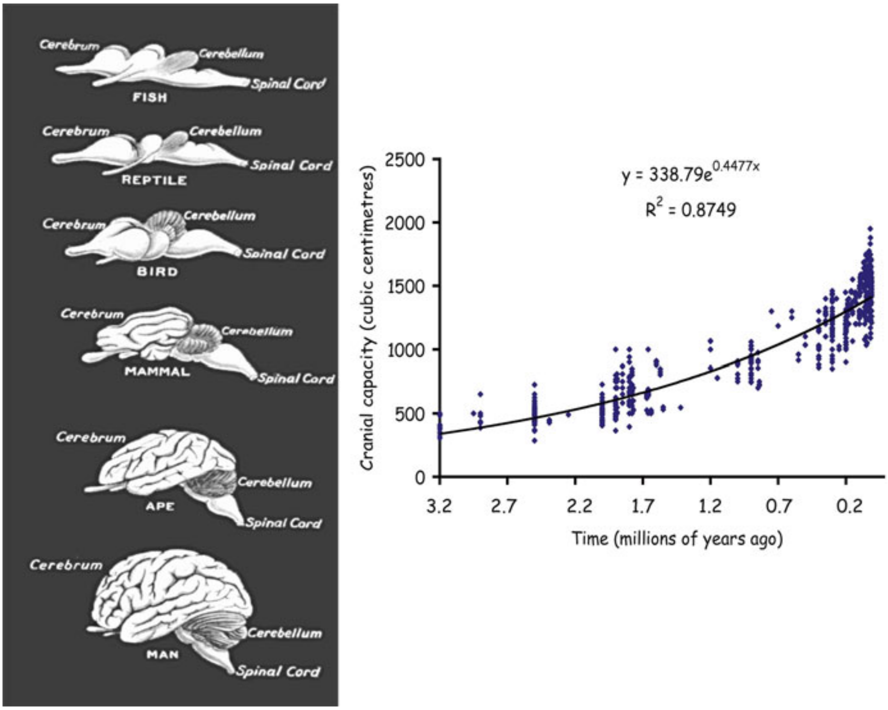


Fig. 3.7 Changes (*left*) in the proportions of the cerebellum (responsible for basic functions) and the cerebrum (responsible for thinking and reasoning) in the brains of fish, reptiles, birds, mammals other than primates, great apes and man. The cerebellum has increased only a little, whilst the cerebrum is almost absent except in mammals and has become very large in humans. Steady logarithmic increase in brain volume (*right*) in hominids has occurred over the past 3 million years. *Homo sapiens* dates back only to about 0.1 million years (From Moss 2012)

environment to suit ourselves. We do it, for example, in the building of sophisticated shelters, of transport that can take us rapidly away from danger, and in the domestication of other species to give us readily available, highly nutritious and storable food.

We are still prisoners of our biology, nonetheless. We are driven by our genes to behave in ways that have exact parallels with all other species. In dangerous situations we will favour those with whom we share genes, our families; in general we will attempt to acquire and hide food and other resources against future adversity; we will avoid mating with close relatives, for there are dangers of proliferating deleterious genes in doing that; and we will plot and plan to better ourselves. We have been described as deceptive and scheming apes (Rowlands 2009). Yet we are capable of heroic and selfless thinking too. But at the bottom, an invasive, deceptive, scheming species that has become partly independent of natural selection is a great danger to its own survival. The plot of the evolutionary play has turned towards the potential destruction of the environmental theatre.

3 Climate Change as Part of a Single Problem

3.1 Four Components

Every play has subplots and there are four in ours (Fig. 3.2), all strongly linked with one another so that there is no particular order of importance on a global scale. In an interlinked system, a nexus, all are ultimately about equal. In the top left of Fig. 3.2 is climate change. There is almost complete scientific consensus that the climate changes over at least the past 60 years and probably over the last 150 have been driven by human activity. There is ample visual evidence of change, not least in the almost universal melting back of mountain glaciers (Fig. 3.8) and the erosion of coastlines from the rise in sea level. Independent sets of temperature and rainfall measurements (IPCC 2014) give similar overall trends. Records of the dates of freezing and thawing of lakes also confirm the warming. Causative mechanisms are well understood; the basic physics is clear. Greenhouse gases intercept heat radiation reflected from the ground at rates proportional to their concentrations in the atmosphere. As concentrations increase, more radiation is intercepted before it can be lost to space. There are very good series of data for these gases, derived from direct observations in recent centuries and from bubbles of air preserved in Antarctic ice cores for time spans of up to a million years. They all show a steady increase as human populations have burgeoned.

Fig. 3.8 Photographs of the Muir glacier in Alaska taken from the same place in 1891 and 2005

Persistence of life on Earth in its present complexity depends on a greenhouse effect. Before it developed, Earth was populable only by limited groups of microorganisms. Without a moderate greenhouse effect, Earth would have an atmosphere somewhere between the intense cold of Mars and the high heat of Venus (Lovelock 1965). It is an enhanced greenhouse effect that is the problem now, or rather it is the speed with which the effect is changing: about 30 times faster than any such changes in the geological past (Lenton and Watson 2011). Furthermore, the ecological systems that have tempered such changes in the past are in decline as a result of other of our activities. We have destroyed nearly three quarters of these systems on land, replacing them with agricultural and urban systems, which make very little contribution to carbon regulation. Fortunately the living systems of the ocean, which although also damaged by the acidification that has come from absorption of carbon dioxide, have been affected to a more limited extent, are also part of the regulatory system and have helped prevent the even greater changes in the atmosphere that can be predicted from the rates of fossil fuel burning. The steady rises in concentrations of greenhouse gases that we are now measuring in the atmosphere, like the rising temperature chart of a fevered patient, suggest that the remaining natural systems are not coping. We are already past an important danger point (Rockstrom et al. 2009).

3.2 Profligacy

The top right of Fig. 3.2 includes some of the consequences in the developed world of our having a larger brain and being able to modify our circumstances. We create a comfortable environment for ourselves, but one depending very heavily on raw materials, including fossil fuels, that are not replaceable and whose use has increased the carbon dioxide concentration in the atmosphere. Moreover, through our promotion of an economic system that dismisses environmental costs as externalities and favours economic growth at all costs (Costanza et al. 2009), we have allowed ourselves a lifestyle that is damaging (Lawrence 2004). Our life expectancies have increased, but so have our medical problems. We have to die, but in the decades before death, we run up major costs resulting from obesity, diabetes and heart disease (Swinburn et al. 2011) that have been increasing because of diets conditioned by the profit motive rather than attention to our natural biology. We insist on costly control of our building environments and increasingly isolate ourselves from the natural environment. Our children, mesmerised by the products of our technologies, have less contact and awareness of our dependence on natural systems. This compounds the problem because new generations have reduced connection and sympathy for the environment that they damage (Louv 2010). Together with the pre-eminence of gross domestic product, which rises with increasing environmental damage and expenditure on health care, we have a problem with strong positive feedback.

3.3 Poverty

At the bottom left of Fig. 3.2 are problems arising in the less-developed world: those of poverty, partly instigated by the developed world in making and recovering hard currency loans for prestige projects, and compounded by an inability to pay for adequate medical treatment. Poverty is increased by corrupt governments, often supported by developed nations in the interests of furthering their economies through guaranteeing supplies of raw materials, and by extreme inequalities. Poverty is also intensified by many small wars, caused by the unrest internally generated by these inequalities and the support, by the western governments of regimes that work, however corruptly, in western interests. Some of these countries are already arid, where the effects of climate change, especially on water supplies, are extreme.

The developing world has previously shown the greatest population increase. Death rates have declined through the diffusion of public health measures, but birth rates have remained high for several reasons. These include religious belief and the need for large families to provide security for older people by providing labour. Birth rates are now declining in many countries, owing to better education of women, but economic insecurity is still a major problem. The global population continues to increase but there is a new component coming from greater longevity in the developed world. This longevity is still increasing and is equivalent to a further decrease in death rate. Obesity effectively also contributes a population effect and is greatest among the poor in developed countries (Drenowski and Specter 2004). The latter authors calculate that the extra resources needed to maintain the extra biomass in larger bodies in the developed world are the equivalent of those of perhaps half a billion more people.

3.4 Destruction

Increasing populations, the need for more food in the developing world and adoption of more extravagant lifestyles in the developed countries put pressures on land. So do the drying effects of climate change. Forests are cleared for agriculture, wetlands are drained, water is polluted and the atmosphere is acidified by fossil fuel burning and the volatilisation of ammonia from intensive stock rearing and vehicle emissions. The fourth group of problems, on the lower right of Fig. 3.2, concerns the conversion of about 70 % of natural biomes (a collective term for systems of ecosystems characteristic of particular climate regimes) to anthromes, lands dominated by human activity (Ellis 2011). Anthromes provide food production, living space and human amenities, but they do not provide ecosystem services such as the regulation of atmospheric gas composition, purification and storage of water, coastal protection and amelioration of local microclimate. They often need to have artificial systems, like dams and water treatment plants to compensate for what has been lost or damaged by other human activities. Nor do they support human mental health as well as biomes do (Fuller et al. 2007). They may even be damaging and not just neutral, for example, by oxidation of carbon stores in arable soils. Much original biome has been converted to pasturage for stock. Meat production not only removes the original services that the land provided but adds more pressures (Foley et al. 2011; Fiala 2008; Westhoek et al. 2014). It takes large amounts of plant food that could be used for feeding human populations and large amounts of water. Meat is not a necessary part of human diets but adds variety and should not be denigrated per se; but meat consumption by developed societies has become so high as to be impacting on the health of those societies as well as on the welfare of societies in the developing world.

Destruction of natural biomes thus has ramifications for the other groups of problems; all the problems are strongly connected and reinforce one another. Hitherto solutions to this nexus of problems have not emerged from the conventional governance of the world's nations. The characteristics of the scheming and deceptive ape have predominated over the possibilities that a large brain offers. Our societies are increasingly disrupted by this conflict and it is time for new thinking about the organisation of human socio-economic systems. Some guidance might come from a study of the characteristics of complex ecological systems, which have been resilient to change and persisted for hundreds of millions of years, in contrast to the few hundred years in which major problems have already developed in human systems.

4 Ecosystems and Human Systems

4.1 Ecosystem Structure

Ecosystems and human systems, such as cities, have much in common (Fig. 3.9). Both have a structure: rocks, water, soil and vegetation in ecosystems; bricks and mortar, concrete, glass and tarmacadam in cities. In that structure are the niches in which different species, or different jobs and professions, find their roles. There needs to be a diversity of species or roles for efficient functioning, and some mechanism, selection or governance, for preventing a subgroup from dominating; otherwise functioning would be compromised. Both systems need energy, almost entirely ultimately from sunlight in both cases. Both produce wastes and that is where they start to differ. Ecosystems recycle almost all of their wastes either within themselves or in adjacent ecosystems and recover energy from the processes. Cities must either export their wastes to microbial ecosystems for removal or use energy to burn them. But overall the parallel is close. Sometimes cities profitably emulate natural processes. The city is dependent on ecosystems for its operation. Its food may come from agricultural land, but the pollinators of the food plants and the control of the pests of those plants are to a greater or lesser extent in the hands of ecosystems

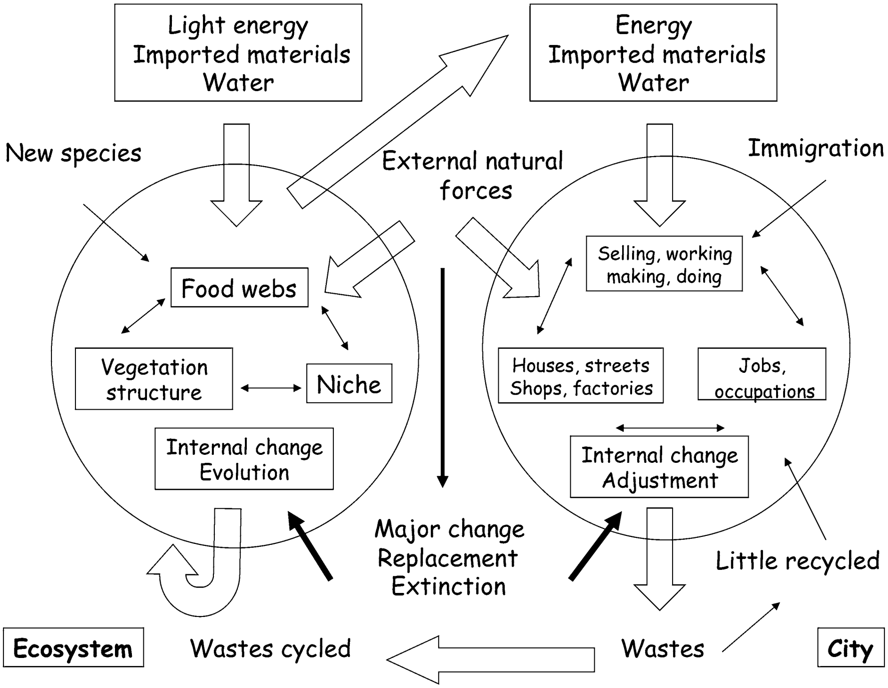


Fig. 3.9 Parallels between ecosystems and cities (From Moss 2012)

adjacent to the farms. A pristine ecosystem is however entirely independent of any human help. It regulates and manages itself and has done so for very long periods. There is much we can therefore learn about how complex systems operate, and about how to create sustainable human societies, from a study of undamaged and unmanaged ecosystems. They have three key characteristics. The first is that scarce chemical resources are used parsimoniously, second that there is an intact characteristic structure (this will include the physical structure and the food web structure) and third that the system is not artificially boundaried but has connections with adjacent ecosystems, so that effectively it is part of a larger complex of systems.

The role of chemical elements is of great importance. Nitrogen and phosphorus are often the scarcest resources needed, and an analysis of pristine soils and waters will reveal vanishingly small concentrations (Smith et al. 2003). These elements are held firmly in the biomass and when that biomass is decomposed, there are mechanisms for the released nutrients rapidly to be intercepted and built back into the biomass before they can be washed out of the system. Waste is not a concept that is applicable to ecosystems. Recycling is routine. This parsimony of nutrient use is associated with a maximal biodiversity, characteristic of the local circumstances (Tilman et al. 2014). There is no absolute standard for diversity. It will be naturally lower (though still vastly higher than most non-ecologists imagine) in the more variable of environments and higher in steady ones, but it is always reduced when nutrients are profligately available.

This is because such circumstances allow competitive species that are fast growing to monopolise the supplies and displace less competitive species. That might seem a perfectly acceptable situation for the proponents of market economies, but there are disadvantages to reduced diversity in that when environments change there needs to be an insurance policy of species that can accommodate the new conditions (Cardinale et al. 2006, 2012). Resources are also wasted when diversity is low. A diverse community is able to find ways of exploiting every source (Tilman et al. 2014). When forest is converted to much less diverse agricultural land, there is enormous leakage of nutrients that has to be compensated for by annual fertilisation. Steady environments can support a very high diversity because species can avoid competition with each other by specialising and forming intricate mutually beneficial relationships. Difficult environments, with rapidly changing conditions, for example, extremes of weather, are not predictable enough to allow such specialisation. Species must be flexible and able to accommodate much change from year to year. This means that the resources available (space, food, water) can only be safely allocated to fewer, more generalist species. In the city analogy, steady predictable conditions allow great diversity of jobs and professions. A pioneer community or a city under pressure may be forced to eschew esoteric occupations. Under siege, most of its inhabitants might have to be in the military. The lesson is that maximal diversity is desirable. Uniformity leads to instability (Scheffer et al. 2009, 2012).

It is a mistake to talk about balance in ecosystems. The balance of nature is a concept that was abandoned by professional ecologists decades ago; environments change so much that equilibrium is never reached. But there are mechanisms that help keep the system functioning and persisting. Were plant eaters to become too abundant, the structure of the system and the physical nature of its niches would be undermined. Parasites and predators check plant eaters. There is no prior design about this. It has arisen through natural selection. Selection makes for efficient predators and efficient avoiders of predation and there is a continuous ‘arms race’ on both sides. But the structure is preserved by it (Estes et al. 2011) and populations do not become so large as to threaten it. Likewise overexploitation by a predator or parasite would threaten its own existence by possible extinction of the host or prey. Persistent human societies likewise should not allow overexploitation. Overexploitation of power or financial might leads eventually to revolt, revolution and collapse, as experienced in France and the British American colonies in the eighteenth century and most South American countries since.

The physical structure of the ecosystem, including its weather, is also important. Floodplain ecosystems, for example, depend for their function and persistence on the seasonal rise and fall of the water. If this is modified through drainage, the floodplain communities are lost and with them the ability to store and purify floodwater (Moss 2010). Removal of forest converts land to a less structured grassland, whose soils erode more readily and whose streams warm up to the extent that fish communities may greatly change. Melting of glaciers changes the stream structure downstream and may threaten human communities with flash floods. Removal of the woody debris that naturally accumulates in headwater streams and rivers results in loss downstream of leaf litter on which the river invertebrate community and subsequently the fish community depends. In cities, loss of structure always leads to problems, from the extremes of war to the social difficulties of shantytown suburbs.

Thirdly, no pristine ecosystem is isolated. Our long history of enclosure in lowland Europe and America gives the impression that boundaries and discontinuities are normal. They are not. Pristine ecosystems merge seamlessly into one another. The lines on maps that separate tundra from boreal forest, boreal forest from deciduous forest and deciduous forest from grassland are myths. The original landscape was continuous and this promotes several features of resilience. It accommodates sufficient territories for large animals to maintain a varied enough pool of genes to avoid inbreeding; it allows movement of organisms so that a local disturbance, such as a forest fire, can be accommodated by emigration and compensated for later by new immigration. Annual migrations, which completely belie boundaries, are also part of the survival strategies for many birds, mammals and flying insects, and in rivers for fish. Human- created barriers (fences, tracts of agricultural land, dams) may prevent these and lead to decline or loss of population. Where any of these three characteristics (parsimony of nutrients, structure, connectivity) have been lost from ecosystems, there has been loss of function and ecosystem services provided. Generally some sort of management has then to be provided to compensate and maintain either structure or populations of particular species, but a need for management is always an expression of failure to preserve an intact self-maintaining system.

4.2 The Problem of Invasive Species for Ecosystem Structure

One particular problem for our remaining ecosystems is particularly germane to this comparison between natural and human systems. Movement of exotic species has been made easier by commercial activities (the import of pets and garden plants) and accidental transport as contaminants in cargoes or in ballast water of ships. Invasion of new species is an essential property of ecosystem maintenance because it helps resilience towards change by sometimes providing a better-fitted species to new circumstances. After the ice retreated northwards in Europe, from 15,000 years ago, it was such invasion that allowed recolonisation of the newly bare land; new establishment was then easy but became more difficult as the new communities became established.

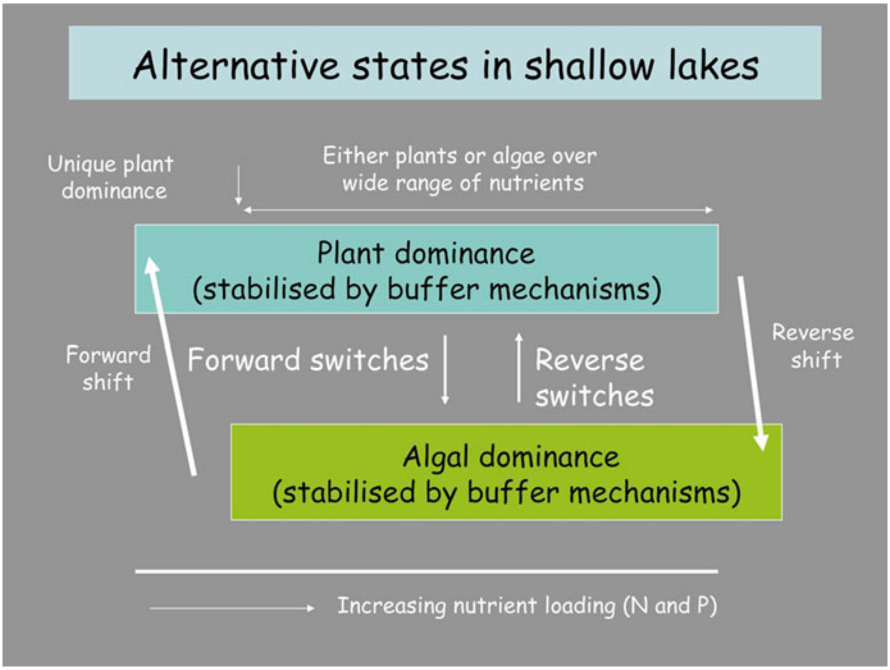
The problem now is that species can be more rapidly moved than ever before, over long distances, into starkly different communities. Many such species are highly competitive and tough (Levine et al. 2003), for such species are those that lend themselves to the vicissitudes of association with human-dominated systems. They are imported without the associated competitors, predators and parasites that controlled their numbers in their native habitat, and they may thus easily establish and displace native species in the new habitat. Typically their populations grow rapidly and are easily dispersed. We are just such a species, and the widespread damage to natural communities and high rate of extinction of other species now being observed are symptoms typical of such invasions. Our populations are rising; we have eliminated controls that kept populations of early hominids in check (predators, diseases, food shortage). Our basic biology underlies the problems we create.

4.3 Alternative States

There is a further characteristic of ecosystems that is relevant in considering human systems. For any given place and time, no single system has a monopoly. A tract of forest will be very patchy, reflecting sometimes small differences in microclimate or terrain, but also the random accidents of past local extinction and recolonisation. A fire or flood, or the passage of a grazing herd, will have influence for many generations. This patchiness is normal and may sometimes be dramatic. A fire may clear an area and grazers will come to the more open grassy habitat in the aftermath and may stay. They may then, through their grazing, keep the area as open grassland for a very long time, biting back any developing tree seedlings. Grasses grow from the base of the plant and are not so vulnerable. There will then be two alternative states for such a patch: forest or grassland. Alternative states have been described for many situations (Scheffer et al. 2001; Scheffer and Carpenter 2003), and ecological theory has developed to extract the common features of the phenomenon.

Any particular state will persist for a long time, maintained by stabilising mechanisms (buffers) against change. For example, in a shallow lake (Moss 2007), clear water and dominance by submerged plants will be stabilised by small animal grazers that keep microscopic algae from growing and shading out the plants. The plants provide refuges to these animals against their fish predators because fish will not easily be able to hunt in dense tangles of plants. The plants also secrete substances that inhibit algal growth. In contrast a turbid-water algal-dominated state is also possible under similar external conditions. The algae once established are able to prevent plant growth through shading and maintain open-water conditions where the grazers find no refuge from fish, and in which the fine amorphous sediment, laid down by the algae when they die, smothers plant seedlings growing on the bottom.

Either of these states can exist over a range of environmental conditions, epitomised in lakes by the availability of nutrients (Fig. 3.10). The communities will differ in the detail of what particular species persist depending on the nutrient concentrations, but the distinction of large plant domination in clear water or microscopic algal dominance in turbid water will be maintained. It is possible to switch between states or for there to be a spontaneous shift between states. A switch is imposed from outside, so that, for example, a major storm, a rise in water level, introduction of vigorously plant-grazing fish, birds or mammals or pesticides that kill the small animal grazers will so damage the plants that the algae can take over. The reverse switch can be achieved by removing fish and allowing development of



Alternative states in shallow lakes

Unique plant dominance

Either plants or algae over wide range of nutrients

Plant dominance (stabilised by buffer mechanisms)

Forward shift

Forward switches

Reverse switches

Reverse shift

Algal dominance (stabilised by buffer mechanisms)

Increasing nutrient loading (N and P)

Fig. 3.10 Alternative states in shallow lakes

large numbers of small grazers or sometimes by lowering the water level. A shift has a different character. At the extremes of nutrient concentrations, there may be a spontaneous change not requiring an external driver. A very large concentration of nutrients may thus give algae such great advantages that the system flips to algal dominance, or alternatively a very low concentration may be unable to support enough algae to shade the plants, whose access to nutrients in the sediments through their roots gives them an inherent advantage. Points where shifts occur are called tipping points and the obvious application of this knowledge to human societies lies in the parallel that there is more than one way of organising a society, that it may be changed through deliberate action and that at certain extremes it may spontaneously shift (Fig. 3.11).

4.4 Alternative States in Human Societies and Sustainability

The world is increasingly dominated by western technological society. It is this state that is behind most of our problems, not least its demand for convenient and cheap energy that is causing rapid climate change, its destruction of natural systems in the interests of its economies and its excesses now resulting in self-imposed health problems. A recent UK Government Report found that nearly half of the English

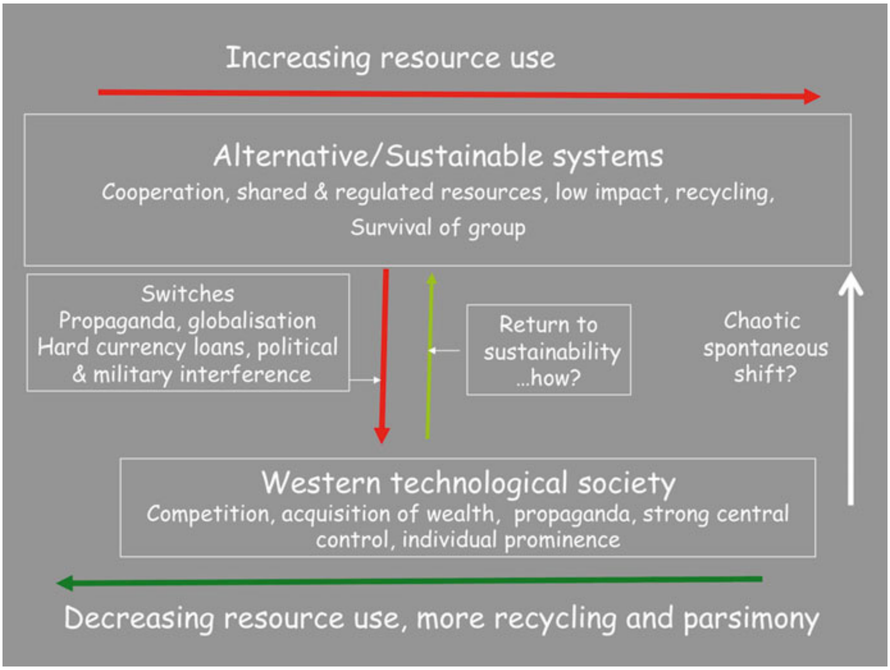


Fig. 3.11 Alternative states in human societies

population was continually taking medicines for depression, high blood pressure and other maladies of an indulgent lifestyle (Health and Social Care Information Centre 2014). Almost everyone is now agreed that such problems need to be avoided or contained, and talk of a 'sustainable society', posited by the Brundtland report, is common. Achievement of that society is proving elusive, however, and if we equate western technological and sustainable societies as alternatives over a gradient of resource (energy, water, minerals, food, space) use, alternative state theory from ecosystems may give us an explanation of why such a switch or shift is proving so difficult.

A sustainable society is one that is not causing rapid changes in climate; that is recycling its material resources; that does not suffer the unrest caused by unemployment, poverty and disease; and that has a stable population. Because all of these characteristics are weakened by destruction of natural ecosystems, and because humans are living organisms with similar dependency as other species on such systems, it will also be one that preserves natural systems and restores those that have been damaged.

Voluntary solution of the problems, by converting to a low-carbon energy economy, restraint and recycling, encouragement of healthy diets and minimisation of food wastage would go a long way towards reaching a shift but is currently resisted by the buffer mechanisms that preserve the western technological system. These buffers also resist a deliberate decision to switch at some intermediate point on the

Fig. 3.12 Pile of buffalo skulls waiting to be ground into fertiliser in the 1870s. The American buffalo was ruthlessly shot on the American Great Plains in an attempt to drive out the traditional plain Indian tribes, which depended on it for food and skins. The species almost became extinct with only 11 individuals left at the nadir. Burton Historical Collection, Detroit Public Library

curve. The buffers include the use of GDP as a measure of human progress, political systems dominated by politicians whose world-view is limited by an education almost exclusively outside the environmental arena and lobbies hugely financed by sectoral commercial interests (Klein 2014; Monbiot 2000). Nor does it help that a sustainable society is derided through propaganda as one of primitivism and discomfort, a modern version of Thomas Hobbes' (1651) 'No arts, no letters; no society; and which is worst of all, continual fear of violent death; and the life of man, solitary, poor, nasty, brutish and short'.

We have some insight into aspects of a sustainable society from a study of the traditional societies that have been switched to western technological society by such mechanisms as hard currency loans and trade impositions (coca-colonisation), military action and destruction of the natural systems on which they depended (Fig. 3.12) (Moss 2012). From anthropological studies, it is clear that survival of the group above the individual, cooperation rather than competition, moderation in use of resources, recycling and avoidance of overexploitation and sharing rather than retention of individual gains were common features, not necessarily consciously imposed but determined by the consequences for survival of ignoring them. In contrast western technological society places its emphasis on freedom of the individual to exploit others and profligate resource use to bolster growth economies. This is manifested in promotion of GDP (Porritt 2007), market competition to sell more, planned obsolescence, new models, annual fashions, high turnover, centralisation of wealth and power in the interests of economic expansion, international uniformity (not least globalisation of markets), intensification in agriculture (Tudge 2003; Lawrence 2008), commercial colonisation, treatment of natural resources as exploitable commodities, externalisation of environmental costs and favourable propaganda through education.

If either a steady movement towards a positive tipping point or a deliberate switch towards sustainability is unlikely in modern human societies because of the strength of the buffers opposing them, ecological theory would suggest two further possibilities. The first would be an intentional weakening of the current buffers that prevent change and the second an uncontrolled switch enforced by some crisis and breakdown in the current western system. The first possibility is most desirable and how to achieve it is the topic of the fifth part of this paper. The likelihood of the second, which would be chaotic and unpleasant, poses some interesting speculations as to what might cause it and whether there might be some early warning of it.

4.5 Early Warnings of Tipping Points

Theoretical ecologists have recently been active in seeking indications of a coming shift or switch (Scheffer et al. 2009, 2012; Scheffer 2010) and there is a limited amount of experimental work to test the theory. A tipping point is heralded; it is predicted by greater variation (instability) in a system and a slowing in the rate of recovery following a small perturbation. In cultures of a cyanobacterium, which is intolerant of high light intensity, pulses of intense light were given and then the growth rate of the culture followed as it recovered (Veraart et al. 2012). The rate of recovery decreased progressively during a series of pulses until eventually the culture failed to recover at all. We can speculate that several features of the human socio-economic systems of Earth are showing increasing instability and slowness to recover from disturbance (Barnosky et al. 2012). Economic growth rates following the banking crisis of 2008, successive attempts to eradicate fundamentalist terrorism and cumulative effects of increasingly repeated extreme weather events might be examples.

Another line of research has looked at the characteristics of resilience in complex systems. The theory predicts that systems with a high diversity of components that are loosely linked will have greater resilience compared with systems that have similar components that are strongly interdependent (Fig. 3.13). This connects well with a large body of research that shows that ecosystem process like photosynthesis or decomposition increase in amount and efficiency with increasing species diversity (e.g. Cardinale et al. 2011). Pressures on a resilient diverse system result in a progressive change and adaptation to the circumstances; similar pressures, on a system of relative uniformity and high internal dependence, result in little change at

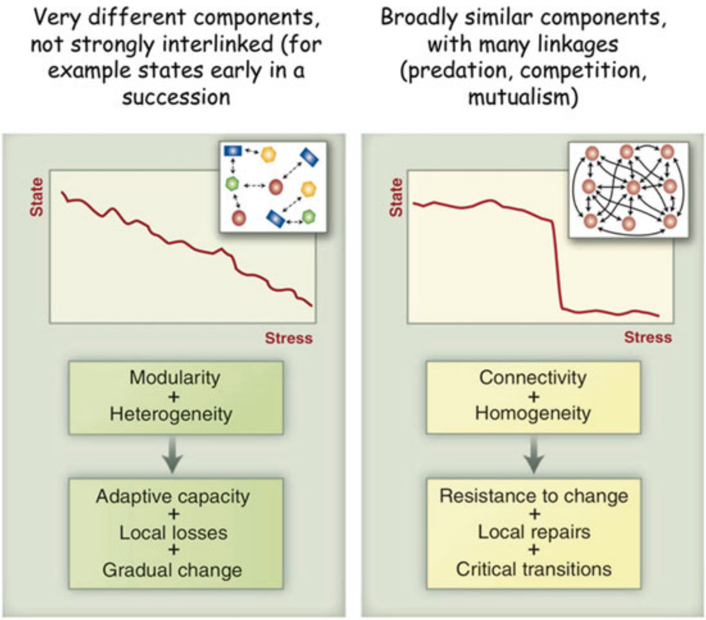


Fig. 3.13 Systems that have diverse components, loosely linked, are likely to change steadily when subjected to pressure. Systems that have broadly similar components, tightly linked, are more likely to undergo catastrophic change (From Scheffer et al. 2012)

first but then a precipitous collapse, a tipping, to a very different system. Pristine ecological systems are of the first kind (Brook et al. 2013). Damaged systems in which many of the components have been lost are of the second kind. Human socio-economic systems used to be of the first kind, reflected in a huge diversity of traditional systems appropriate to different environmental circumstances. The uniformity promoted by increasing globalisation, dominance by a limited number of electronic information systems, control of food supplies by a relatively few international corporations, control of educational criteria through ideologies, religious intolerance and fundamentalism and increasing centralisation are all likely to be characteristics of a system prone to precipitous collapse. The 2008 banking crisis is a salutary example (Haldane and May 2011).

A collapse of human organisations might come from any of a huge combination of circumstances in the web of connections that characterises the four groups of problems that were discussed in Sect. 2, but the linkage between climate change and destruction of ecosystem services must be a prime candidate. As temperatures increase, there is a positive feedback as respiration rates of microorganisms in soils and waters increase faster than photosynthetic rates, and stores of carbon dioxide are released (Moss 2014), whilst decreasing solubility of methane results in major releases from the interstitial waters of melting permafrost. We have no idea how imminent a climatic or any other tipping point might be. It will be far wiser to begin reorganising our societies in a variety of ways to reduce the risk avoiding these possibilities (Porritt 2013). Some of these are discussed in a later section.

5 Strategies for the Future

5.1 Key Issues

I have established four features relevant to the mitigation of the climate change problem. First it is ultimately a biological problem of disruption of a major, biologically determined element cycle by a single evolved species, ourselves. We show characteristics of invasiveness that for other species would have been accommodated through interactions with other organisms during assimilation into natural ecosystems as a functional and not disruptive component. Secondly, we have properties, summed up in a large brain, which can bypass such assimilation and give us the choice of damaging the system, possibly to our demise, or integrating into it in sympathetic ways. This contrast is between the essentially biological selfish part of our nature and the cultural altruistic side, in simple biblical terms, the choice between evil and good.

Thirdly climate change is not a separate problem, but part of a complex of interlinked problems, and ultimately the consequence of our behaving as a biological species. We look after ourselves under the circumstances of the present with little regard for the future, just as does every other organism that is maintained by natural selection. Our problem is to recognise this, for recognition of a problem is the first step to solution. And fourthly we live in complex socio-economic systems that increasingly pretend to distance themselves from natural systems, though ultimately we depend on and can learn from them. They have resilience and, until we began to damage them, had accommodated many changes, including quite catastrophic ones, in the past, and maintained their functioning. Prime among these properties is a high diversity of loosely linked components. Our current societies are becoming increasingly uniform, their local characteristics lost and our institutions diminished in number and nature. Increasingly different parts of the world have become homogenised through agricultural, economic and social systems that have been internationalised to common standards.

The first step in creating a comfortable future for our species has to be a frank recognition that we cannot ignore our biological nature, both in our participation in the biosphere and in the nature of our dealings with one another and with natural ecosystems. Invasive species can be bad news and we need to recognise this property of ourselves and create institutions that curb this tendency. Otherwise we have no future. Given that recognition, we are more likely to create a better strategy for tackling the tangle of climate change, profligacy, poverty and ecosystem destruction.

5.2 Curbing Emissions Is Not Enough

Many people believe that all that is needed to mitigate climate change is to reduce world carbon dioxide emissions from fossil fuel burning. That has proven impossible so far (Monbiot 2006). Annual emissions continue to rise and over 20 years of

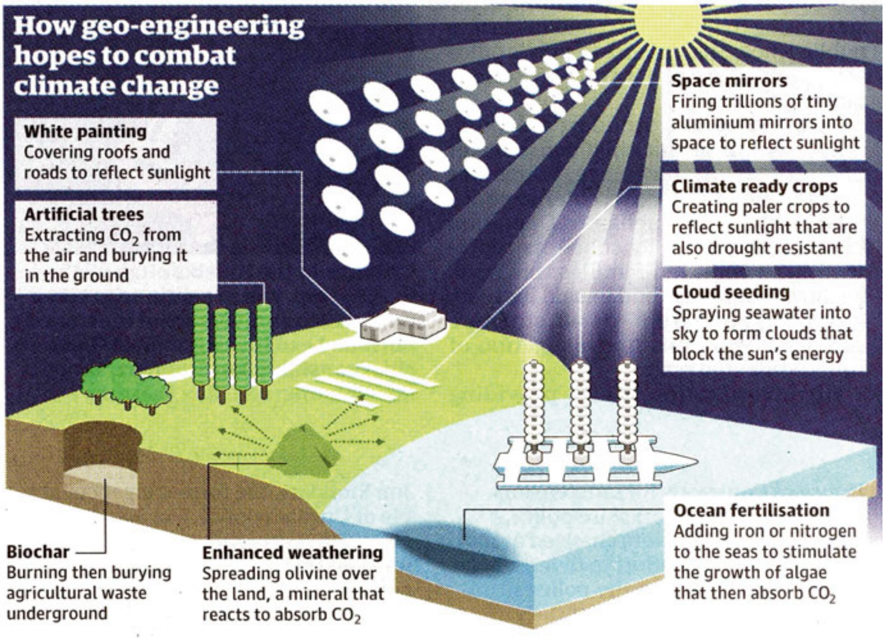


Fig. 3.14 Geoengineering proposals to combat climate change, for the most part by treating symptoms. There is an irony in proposing the creation of artificial trees when real ones are readily growable! Most of these devices are yet to be invented; some would be prohibitively expensive or too localised. Others defy credibility (Drawing from The Guardian 2013)

diplomacy have had little impact. Curbing fossil fuel burning will reduce the rate of temperature rise but will not necessarily stop the warming trend. Temperatures will not stabilise until the annual rate of storage in biomass, peat, waterlogged soils and sediments is as great or greater than the annual net rate of emission. The lesser the success in curbing emissions, the greater will be the need to preserve existing sinks and to create new ones. Hitherto the sinks are calculated to have increased alongside emissions, probably as a result of increased net photosynthesis of land vegetation (Le Quéré et al. 2014), but this process can only go on so long as carbon dioxide limits photosynthetic rates. The calculations are uncertain and mostly made by difference. More recent investigations (Raupach et al. 2014) suggest that the sinks have been declining for some time with the decline hidden in the uncertainty of the calculations. There is a limit to how much a process like photosynthesis can increase. It is determined by its biochemistry and will eventually be limited by water shortage and diffusion rates of carbon dioxide.

The alternatives of global geoengineering (Fig. 3.14) are not adequate substitutes. All may have unanticipated side effects (Stilgoe 2011; Ridgwell et al. 2012); most are not yet even invented or so costly on the scale needed as not to be contemplated. It is feasible to capture carbon dioxide from concentrated sources like power stations or cement factories, but that only partly holds the line. It does nothing for the millions of small domestic and industrial sources; and it does not reduce existing carbon dioxide levels, which are already causing significant problems. Nor has the problem of what to do with carbon dioxide captured from power stations been solved. It is a volatile gas needing to be stored under low temperature or high pressure (and requiring energy to compress it) or as a compound such as carbonate or organic matter, formation of which would require at least as much energy as released from its initial combustion.

In contrast we already have systems for carbon storage, in natural ecosystems, that have been successfully tested over many millions of years, which are continually refined through natural selection, offer additional benefits and services and incur no running costs. Our problem is that we have profligately wasted these systems and continue to destroy them. We can, however, recreate them, at least on land.

5.3 Adaptation and Mitigation Are Connected

The distinction between adaptation and mitigation can be subtle and opens up the question of what adaptation really means. It is variously categorised, from establishing better meteorological recording (Honduras), increasing the spread of advice and information (India, the USA, Mauritius, Kenya), better disaster planning (the Philippines, the USA, Caribbean countries), encouraging traditional farming methods that dealt with the vicissitudes of variable weather in the past (Cambodia, Peru, Sri Lanka, Kazakhstan) and promoting drought-resistant crop varieties (Colombia) to reforesting devastated mangrove areas (Malaysia) and raising sea walls and building storm surge barriers (the Netherlands). Overall, adaptation is sensible and may serve other positive purposes, but it is at best treatment of symptoms and may be little more than a proliferation of discussion and advisory documents, though many have been valuable. It verges on mitigation, however when new habitats, particularly wetlands and forests that store carbon, are created. In the UK, preservation of existing carbon stores in peatlands and tree planting is regarded as adaptation; creation of new stores through restoration of drained wetlands would also be so regarded but it is effectively mitigation for it starts to alter the carbon budget. The problem is that none of these things are contemplated on anything like the scale required.

5.4 The Scale of the Solution

The scale of the solution can be seen by examining the current global net carbon budget (Table 3.1). If we can stop forest destruction (mostly now from conversion of rain forest to oil palm plantations or cattle ranching), but are unable to reduce carbon emissions significantly, we would need an extra 3.4 gigatonnes per year of

Table 3.1 Current net global carbon budget in gigatonne carbon per year. A net budget looks at the consequences of human activities. The gross budget includes the uptake of carbon by photosynthesis and its release in respiration and is much larger, but the two processes are nearly in balance and are therefore conventionally excluded

Emissions	
Emissions from fossil fuel burning and cement manufacture	8.89 ± 0.41
Land use change (forest destruction, drainage)	0.9 ± 0.49
Storages	
Land	2.89 ± 0.79
Ocean	2.59 ± 0.49
Surplus build up in atmosphere	4.31 ± 0.11

Based on Le Quéré et al. (2014)

carbon storage on land or in the ocean. The only possibility of increasing ocean storage is by increasing ocean production by fertilisation with iron, but there is no guarantee that the extra production would be stored as sediment and not respired back into the atmosphere. Marine phytoplankters require about 10 µmol of iron per mole of carbon (Morel et al. 1991), so this might mean dumping about 190,000 tonnes of iron into the oceans. Some would be recycled but most would enter the sediments, so annual dosing would be needed. The amount is more than one-sixth of annual world iron production and would require large amounts of energy to deliver it widely over the ocean basins. The uncertainties over ocean acidification and the increased capacity for absorbing solar radiation of the increased algal production make this a risky proposition.

More feasible would be re-establishment of fully functioning land ecosystems on areas that have been converted to anthromes. It would mean more than doubling the present area of natural biomes. The total world land area is about 149 million km^2 of which about one quarter, 37 million km^2, still has reasonably intact biomes. An additional 43.5 million km^2 would be needed and this in the areas that potentially support forest or tundra, where high biomass or organic soils can be supported. Floodplains that have been drained for agriculture are prime for conversion. About one-third or more of the current anthrome area (Fig. 3.15) would be needed if carbon emissions remain at present levels and if current forest destruction ceases. If carbon emissions can be greatly reduced, a proportionately smaller area would need restoration.

There are strong arguments for large-scale restoration on the grounds also of provision of other ecosystem services as well as carbon storage (Monbiot 2014). These include storage and purification of water that can be tapped when rivers run out of the biomes into the anthromes and amelioration of local weather in dry areas (Makarieva and Gorshkov 2006; Sheil and Murdiyarso 2009). The current rate of loss of biodiversity will also be reduced or even reversed. The major cause of biodiversity loss is habitat destruction. Natural biomes with complete food webs, moreover, provide rich cultural values for tourism. Studies that have costed the values of ecosystems have invariably found them more valuable to society as a whole when they are intact over development of them for individual gain (Balmford et al. 2002).

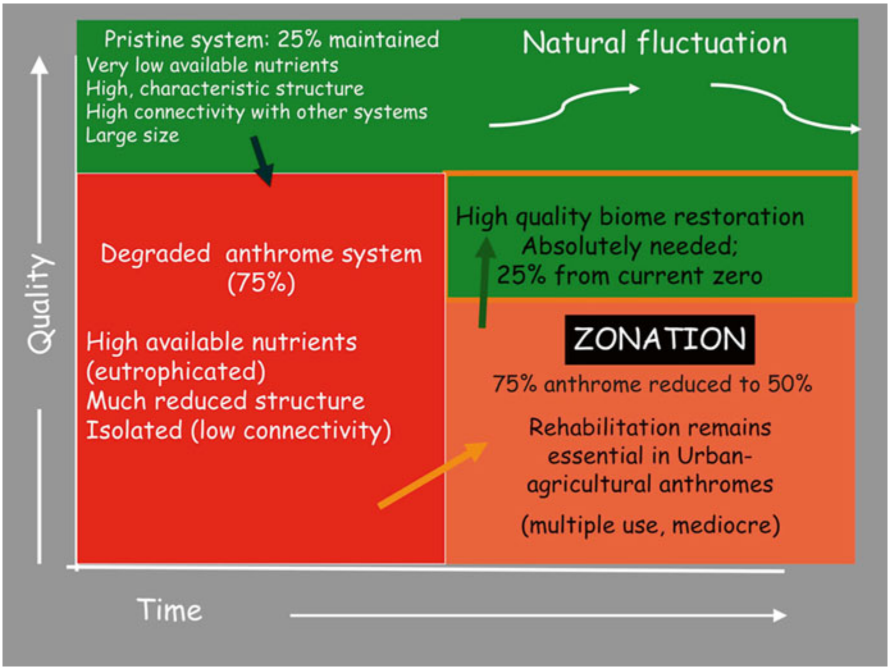


Fig. 3.15 The balance (*left*) between pristine biomes (in *green*) and anthromes (*red*). Currently we sometimes rehabilitate anthromes to counter local problems, improve amenity or improve biodiversity (*orange*) and multiply use such areas. In general this leads to mediocrity of function. But we need to rezone and restore about one-third of this anthrome area to functioning biome to create essential carbon storage (*green* area, *orange* boundary)

Such restoration is not necessarily practicably difficult if done in areas adjacent to existing intact systems by allowing them to grow outwards. It is more difficult recreating such systems in isolation. Natural ecosystems are much more capable of extending themselves if given the chance than we are of creating them de novo, and such conversion can be begun on an individual national basis. It does not initially require international agreement, though poorer countries will need financial compensation for potential lost revenues from richer countries, an issue that has delayed any substantial plans to curb carbon dioxide emissions, but there is an existing basis in the REDD (Reducing Emissions from Deforestation and Forest Degradation) Programme. Its effectiveness, however, has yet to be proven.

5.5 *Grand Strategies Are Needed*

It is easy to diagnose that restoration of large areas of natural biome is likely to be needed; the carbon budget is irrefutable; but it is more difficult to find ways of doing this. We are a selfish, invasive species. We find it difficult to look after the group, easier to look after our individual interests, and this applies to nations also. But there are global realities to face. In confronting them we may mitigate all our problems not just those of climate change but we need first to plot a pathway.

Acceptance of humans as a biological species requiring the same conditions in the biosphere as all others, and not as some independent master of the world capable of manipulating everything to human aspirations, would be a major first step. No biologist would deny it, but many trained in engineering, economics and social sciences find it difficult to embrace their biological nature, and it is these groups who largely control human societies. Given the biological realities, what are the second and subsequent steps? Reduction of carbon emissions is mandatory, with replacement of them by renewable energy sources. Renewable energy sources may not be able entirely to replace fossil fuels, but the solution is to conserve energy, to consider how we might use less and not to continue mining and burning. We are finding reduction of emissions difficult, so a parallel step has to be reconstruction of carbon stores as discussed above. In turn this requires restoration of biomes from large areas of agricultural and even urban land at a time when our population is still growing.

Steady population numbers cannot be achieved, other than by voluntary means, without major social disruption. There is a need to create incentives for smaller families but also to curb obesity, which means overcoming poverty, and to rid ourselves, in the developed countries, of the myth that death can be avoided indefinitely by expensive and technologically invasive medical care. We need to accept that we will die and that there is no great personal advantage to living a dependent and demented life to the age of 120. We need to divert our resources to creating security of tenure and support for poorer peoples and to increase their life expectancy, not prolong it any more for the rich.

Release of land for restored biomes means that we must farm smaller areas, and since there are problems in extreme intensification of agriculture (e.g. side effects of pesticide use on pollinators, oxidation of soil carbon stores and pollution of water supplies), we need to change our farming to ways that are more sympathetic to soils and waters and ideally contribute some carbon storage—and all this at a time when the human population is growing and the pundits of food security are claiming a need for greater agricultural production. But that is to see only a part of the problem in isolation. Reduction of profligacy in the developed world and avoidance of lifestyle diseases mean a change in diet and a removal of the partisan pressures that the relatively few large companies that control food security are currently able to exert through monopoly. Diversity is always advantageous. Diets that have much less meat, much more plant food and much less fat and sugar offer health benefits and savings in medical care and human suffering.

Moreover we waste a great deal, 30–40 % (Lobell et al. 2008; Godfray et al. 2010), of the food we produce, through poor storage in the developing world, processing and marketing practices in the developed (Lawrence 2004, 2008). There is scope to support even an expanding population on much less land than we currently farm. We may need to contemplate reducing our urban areas also, or at least compacting them so as to guarantee the continuity that natural biomes need for independent function. Our cities are often sprawling (Seitzinger et al. 2012). It should be possible to redesign them to be more energy efficient and pleasanter to live in and interfingered with seminatural buffer land for the adjacent biomes, or low-intensity farming and gardens. We may have to give up the idea, in some countries, of large personal gardens with unproductive lawns, in favour of vegetable gardens, allotment plots and roof gardens, but we have imaginative architects for whom this would be a welcome challenge.

To make these changes needs reform of governance (Biermann et al. 2012). Our present organisation is far from democratic, with strong international corporations determining that we remain in a collectively perilous situation (Monbiot 2000; Klein 2014). They have undue influence on a collection of weaker national governments dominated by individuals largely focussed on supporting an economic system that is unsustainable. There is only nominal presidency by a largely powerless, though entirely positively meaning, international organisation, the United Nations, and an electorate (in most countries) that has little power, subjected as it is to propaganda of all kinds through media that are owned by the international corporations. There is substantial understanding of how this system works and how it is linked with our collective problems, but poor, indeed abysmal, communication by academics, who write mostly for themselves, and suppression of this information by sidelining of its caretakers (Martin 1999). In too many countries, there is not even a veneer of democracy.

One step towards the necessary reform of this imbalance of power could be very effective in pushing it towards a desirable tipping point before some more catastrophic one is reached. This would be replacement of GDP by the Genuine Progress Index (GPI) or similar measure (Costanza et al. 2009; Pretty 2013). GDP encourages damage to the environment, social systems and health. It includes the expenditure on cosmetic repair but externalises the damage itself and the costs to human societies and the biosphere. GDP has steadily increased since it was invented in the aftermath of World War II as a way of comparing how societies were apparently progressing. It was well intentioned but now it is malignant. It does not measure human progress, only the rampage of a particular model of economics, and is correlated with human welfare only in a move from extreme poverty to a modest standard of living. Beyond that there is no improvement in the human lot as GDP increases (Fig. 3.16). GPI and other alternative indices treat environmental damage and medical and welfare costs as negatives and incorporate features like domestic labour that are hidden to GDP. Comparison of such better measures of human welfare with GDP shows that they have not steadily increased in the way that GDP has but have remained relatively steady (Fig. 3.17). The difference between them is a measure of the increasing extent of our problems.

A key goal has to be the breaking of the current power of large international corporations and its replacement by elected power through stronger national and international governance. We need a taxation system that justly returns an income to societies in compensation for the damage that an exploitative economic system does. Economies can grow and must grow to the extent that population increases, but only after the damage that threatens the future has been paid for. Growth has to be in service not in use of nonrenewable resources. Labour is our greatest commod-

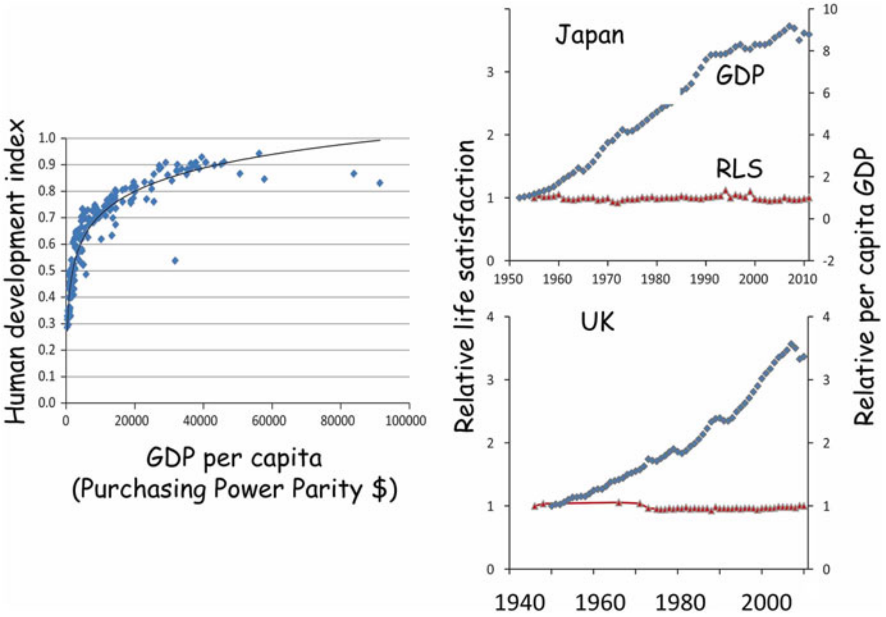
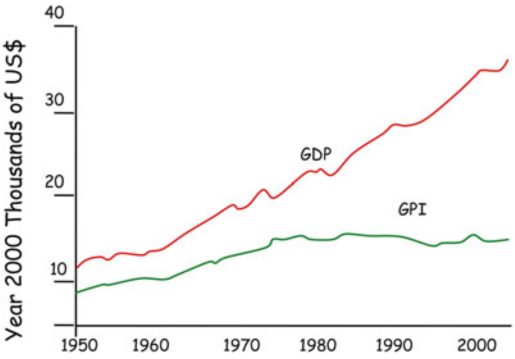


Fig. 3.16 Comparisons between GDP (gross domestic product) and an index of human development based on views of a sample of the populations of the world's nations, plus statistics on health, education and welfare (*left*). Changes in a similar measure (relative life satisfaction, RLS) and in GDP over the past 70 years in Japan and the UK (*right*). Based on Pretty (2013)

Fig. 3.17 Changes in gross domestic product per capita and Genuine Progress Index per capita in the USA since 1950. Based on Costanza et al. (2009)



ity and there is much that can occupy it. Complete reform of economic and taxation systems can only come from a proper recognition of evidence over belief, a stronger role for independent social and natural scientists in government and a better educated electorate, but a start is not impossible even under our present conditions. Our problems are global; in consequence, to echo the thoughts of W. H. Auden, John F. Kennedy and George Monbiot, who headed this paper, our ultimate governance needs to be global also. Indeed we must climb the cross of the moment and let our illusions die; we need to widen our horizons beyond the obvious realities; and we need to abandon the wishful thinking of utopian fantasists.

Acknowledgements I would like to thank two anonymous referees for their useful comments, a huge range of ecological colleagues and friends on whom I have bounced these ideas and received favourable support and Prof. Dr. Hiroshan Hettiarachchi of UNU-FLORES, Dresden, for commissioning this paper and efficiently administering it towards publication.

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Part II
Urbanization as a Main Driver of Global Change

Chapter 4
A Nexus Approach to Urban and Regional Planning Using the Four-Capital Framework of Ecological Economics

Robert Costanza and Ida Kubiszewski

Abstract Ecological economics views our world as an interconnected complex system of humanity embedded in the rest of nature. It is thus fundamentally a nexus approach. It recognizes four basic types of capital assets necessary, in a balanced way, to produce sustainable well-being of humans and the rest of nature. These include (1) built or manufactured capital, (2) human capital (e.g. human labour and knowledge), (3) social capital (e.g. communities, cultures and institutions, including the financial system) and natural capital (resources and natural ecosystems and their products that do not require human activity to build or maintain). Creating a sustainable and desirable future will require an integrated, systems-level redesign of our cities and our entire socioecological regime and economic paradigm focused explicitly and directly on the goal of sustainable quality of life and well-being with minimal waste rather than the proxy of unlimited material growth. It will require the recognition and measurement of the contributions of natural and social capital to sustainable well-being. It is a design problem on a massive scale. An integrated, nexus approach to urban and regional planning and design must be a central component of this process.

The *ecological economics* framework expands the definitions and connects these critical issues. It focuses not only on population size, density, rate of increase, age distribution and sex ratios but also on access to resources, livelihoods, social dimensions of gender and structures of power. New models have to be explored in which population control is not simply a question of family planning but of economic, ecological, social and political planning, in which the wasteful use of resources is not simply a question of finding new substitutes but of reshaping affluent lifestyles and in which sustainability is seen not only as a global aggregate process but also as one having to do with sustainable livelihoods for all within the safe operating space of the global ecological life-support system.

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H. Hettiarachchi, R. Ardakanian (eds.), *Environmental Resource Management and the Nexus Approach*, DOI 10.1007/978-3-319-28593-1_4

In addition a new vision and goals are needed that go well beyond the narrow and inappropriate use of GDP growth as the primary policy goal. There is broad emerging agreement about the overarching goal that should guide sustainable development. There are many ways of expressing it, but the essence is ‘a prosperous, high quality of life that is equitably shared and sustainable’.

There are three elements to this goal that cover the three components of sustainable development—the economy (a high quality of life or well-being), society (equitably shared) and the environment (sustainable—staying within planetary boundaries). There is also the understanding that all three of these elements are highly interdependent and must be satisfied jointly. It is no good to have a high quality of life for an elite few that is not equitably shared or sustainable, or a sustainable but low quality of life where everyone suffers equitably, or a high quality of life for everyone that will collapse in the future. We want all three together in an integrated and balanced way and any one or two without the rest is not sufficient.

It is also important to recognize that the economy is embedded in society, which is embedded in the rest of nature and that these three elements are extremely interdependent. We can no longer treat the economy separately, without considering its dependence on society and the rest of nature.

An integrated, nexus approach to urban, regional, national and global planning must include better, more appropriate measures of sustainable human well-being. These measures need to account for the effects of equity and social and natural capital. The genuine progress indicator (GPI) is one such indicator that shows that in the United States and globally, growth has been ‘uneconomic’ (not improving genuine progress) since about 1980 if one accounts for the social and environmental costs. However, GPI includes only costs and better accounting for the positive contributions of social and natural capital and ecosystem services is also required. These benefits far exceed conventional GDP.

Scenario planning is one technique that can be used to implement these ideas at community, national, and even global scales, but with the added feature of public opinion surveys around the scenarios. Scenario planning creates an ability to discuss and develop consensus about what social groups want. Predicting the future is impossible. But what we can do is lay out a series of plausible scenarios, which help to better understand future possibilities and the uncertainties surrounding them. Scenario planning differs from forecasting, projections and predictions in that it explores plausible rather than probable future and lays out the choices facing society in whole systems terms. There is no simple answer to how to achieve a nexus approach to urban and regional planning, but a critical first step is to develop a shared vision of the goal for the system. Scenario planning incorporating the four-capital model of ecological economics is one way to do this. There is also the growing possibility to employ online computer games and crowd sourcing to build, evaluate, and communicate scenarios.

Creating a sustainable and desirable future will require an integrated, systems-level redesign of our cities and our entire socioecological regime and economic paradigm focused explicitly and directly on the goal of sustainable quality of life and well-being with minimal waste rather than the proxy of unlimited material growth. It will require the recognition and measurement of the contributions of natural and social capital to sustainable well-being. It is a design problem on a massive scale. An integrated, nexus approach to urban and regional planning and design must be a central component of this process.

1 Introduction

UNU-FLORES defines the nexus approach as:

> The Nexus Approach to environmental resources' management examines the interrelatedness and interdependencies of environmental resources and their transitions and fluxes across spatial scales and between compartments. Instead of just looking at individual components, the functioning, productivity and management of a complex system is taken into consideration.

Ecological economics is fundamentally a nexus approach by this definition. Rather than looking only at the economic subsystem, ecological economics is a whole systems, transdisciplinary approach to science and management of our world (Costanza et al. 2014a). This paper lays out some of the basic characteristics and policy recommendations of ecological economics as a framework for a nexus approach to urban and regional planning and design.

A fundamental law of ecology is that everything is connected. We know that this is the case, but putting it into practice is hindered by the disciplinary structure of academia and the sectorial divisions of planning and management agencies. How do we move beyond these divisions to achieve the needed transdisciplinary, nexus approach to urban and regional planning?

In the past we were living in a relatively 'empty world'—a world where humans and their artefacts were a relatively minor part of the system and human activities had only local or regional impacts. However, the world has changed dramatically. We now live in a 'full world', even according to some, in a new geologic epoch—the Anthropocene (Crutzen 2002). We have moved away from an early successional world empty of people and their artefacts (but full of natural capital) where the emphasis and rewards were on rapid growth and expansion, cutthroat competition and open waste cycles. We have moved towards a maturing world full of people and their artefacts (but decreasing in natural and social capital) where the needs, whether perceived by decision-makers or not, are for qualitative improvement of the linkages between components (development), cooperative alliances and recycled 'closed loop' waste flows.

Can we recognize these fundamental changes and redesign our societies and cities rapidly enough to avoid a catastrophic overshoot? Can we be humble enough to acknowledge the huge uncertainties involved and build resilience to their most dire consequences? Can we effectively develop policies to deal with the tricky issues of wealth and income distribution, population prudence, international trade and energy supply in a world where the simple palliative of 'more growth' is no longer a solution? Can we modify our systems of governance at international, national and local levels to be better adapted to these new and more difficult challenges? Can we design and build urban areas, regions, countries and an integrated global society that can provide a sustainable, equitable and prosperous future for all?

To do this requires a transdisciplinary, nexus approach that recognizes the interconnectedness and interdependence of humans with each other and with the rest of nature. The transdiscipline of *ecological economics* (Costanza et al. 2014a) is based on an interconnected, whole systems view of the world and humans place in it. *Ecological economics* can be a basis for developing a nexus approach to urban and regional planning and design. It incorporates a 'four-capital' model of the assets we have to manage in order to achieve this.

1.1 Four Basic Types of Capital Assets

These assets, which overlap and interact in complex ways to produce all human benefits, are defined as:

- *Natural capital*: The natural environment and its biodiversity, which, in combination with the other three types of capital, provide ecosystem goods and services—the benefits humans derive from ecosystems. These goods and services are essential to basic needs such as survival, climate regulation, habitat for other species, water supply, food, fibre, fuel, recreation, cultural amenities and the raw materials required for all economic production.
- *Social and cultural capital:* The web of interpersonal connections, social networks, cultural heritage, traditional knowledge, trust and the institutional arrangements, rules, norms and values that facilitate human interactions and cooperation between people. These contribute to social cohesion to strong, vibrant and secure communities and to good governance and help fulfil basic human needs such as participation, affection and a sense of belonging.
- *Human capital*: Human beings and their attributes, including physical and mental health, knowledge and other capacities that enable people to be productive members of society. This involves the balanced use of time to meet basic human needs such as fulfilling employment, spirituality, understanding, skills development, creativity and freedom.
- *Built capital*: Buildings, machinery, transportation infrastructure and all other human artefacts and services that fulfil basic human needs such as shelter, subsistence, mobility and communications.

So, to implement a nexus approach to urban and regional planning, in addition to the built infrastructure of our urban systems and individual people, we must also recognize and design with our social and natural capital assets in an integrated and comprehensive way. In particular, dealing with the major issues of climate change, urbanization and population growth in an integrated way will be key to designing sustainable and desirable urban systems.

2 Dealing with Climate Change, Urbanization and Population Growth in an Integrated Way

Another way of characterizing ecological economics is by the basic problems and questions it addresses: allocation, distribution and scale.

Allocation refers to the relative division of the resource flow among alternative product uses—how much goes to production of cars, shoes, ploughs, teapots and so on. A good allocation is one that is efficient, that is, that allocates resources among product end uses in conformity with individual preferences as weighted by the ability of the individual to pay. The policy instrument that brings about an efficient allocation is relative prices determined by supply and demand in competitive markets.

Distribution refers to the relative division of the resource flow, as embodied in final goods and services, among alternative people, how much goes to you, to me, to others and to future generations. A good distribution is one that is just or fair, or at least one in which the degree of inequality is limited within some acceptable range. The policy instrument for bringing about a more just distribution is transfers, such as taxes and welfare payments.

Scale refers to the physical volume of the throughput, the flow of matter–energy from the environment as low-entropy raw materials and back to the environment as high-entropy wastes.[1] It may be thought of as the product of population times per capita resource use. It is measured in absolute physical units, but its significance is relative to the natural capacities of the ecosystem to regenerate the inputs and absorb the waste outputs on a sustainable basis. Perhaps the best index of scale of throughput is real GDP. Although measured in value units (P × Q, where P is price and Q is quantity), real GDP is an index of change in Q. National income accountants go to great lengths to remove the influence of changes in price, both relative prices and the price level. For some purposes the scale of throughput might better be measured in terms of embodied energy (Costanza 1980; Cleveland et al. 1984). The economy is viewed as an open subsystem of the larger, but finite, closed and nongrowing ecosystem. Its scale is significantly relative to the fixed size of the ecosystem. A good scale is one that is at least sustainable, which does not erode environmental carrying capacity over time. In other words, future environmental carrying capacity should not be discounted as done in present value calculations. A sustainable scale is one that stays within planetary boundaries (Rockström et al. 2009). An optimal scale is at least sustainable (i.e. it lasts), but beyond that it is a scale at which we have not yet sacrificed ecosystem services that are at present worth more at the

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[1] Scale in this context is not to be confused with the concept of 'economies of scale', which refers to the way efficiency changes with the scale or size of production within a firm or industry or to geographic scale. Here we are using scale to refer to the overall scale or size of the total macroeconomy and throughput.

margin than the production benefits derived from the growth in the scale of resource use.

Priority of Problems The problems of efficient allocation, fair distribution and sustainable scale are highly interrelated but distinct; they are most effectively solved in a particular priority order, and they are best solved with independent policy instruments (Daly 1992). There are an infinite number of efficient allocations, but only one for each distribution and scale. Allocative efficiency does not guarantee sustainability (Bishop 1993). It is clear that scale should not be determined by prices but by a social decision reflecting ecological limits. Distribution should not be determined by prices but by a social decision reflecting a just distribution of assets. Subject to these social decisions, individualistic trading in the market is then able to allocate the scarce rights efficiently.

Climate change, population growth and urbanization are all interconnected problems of scale, distribution and allocation, but the scale problem now looms very large because it has been ignored by mainstream economics and urban planning for so long. Dealing with climate change, urbanization and population growth in an integrated way means first determining an optimal scale that does not damage the climate system and that is sustainable in terms of human population and its urban component. The idea of 'growth boundaries' that has been used successfully in Oregon to control urban sprawl is one example at the urban scale. Then we must design a fair distribution system and an efficient allocation system within the 'safe operating space' that adequately recognize the value of social and natural capital.

2.1 Population and Carrying Capacity

A primary question is: Are there limits to the carrying capacity of the earth system for human populations? Ecological economics gives an unequivocal *yes*. Where doubt sets in is on the precise number of people that can be supported, standard of living of the population and the way in which food production will reach the limit imposed by the carrying capacity.

Various estimates of global carrying capacity of the earth for people have appeared in the literature ranging from 7.5 billion (Demeny 1988) to 12 billion (Clark 1958), 40 billion (Revelle 1976) and 50 billion (Brown 1954). However, many authors are sceptical about the criteria—amount of food or kilocalories—used as a basis for these estimates. 'For humans, a physical definition of needs may be irrelevant. Human needs and aspirations are culturally determined: they can and do grow to encompass an increasing amount of 'goods,' well beyond what is necessary for mere survival' (Demeny 1988). For a long and careful if somewhat inconclusive discussion of the population issue, see Cohen (1995).

Cultural evolution has a profound effect on human impacts on the environment and on notions of well-being and quality of life. By changing the learned behaviour of humans and incorporating tools and artefacts, it allows individual human resource requirements and their impacts on their resident ecosystems to vary over several orders of magnitude. Thus it does not make sense to talk about the 'carrying capacity' of humans in the same way as the 'carrying capacity' of other species (Blaikie and Brookfield 1987) since, in terms of their carrying capacity, humans are many subspecies. Each subspecies would have to be culturally defined to determine levels of resource use and carrying capacity. For example, the global carrying capacity for *Homo americanus* would be much lower than the carrying capacity for *Homo indus*, because each average American consumes much more than each average Indian does. And the speed of cultural adaptation makes thinking of species (which are inherently slow changing) misleading anyway. *Homo americanus* could potentially change its resource consumption patterns drastically in only a few years, while *Homo sapiens* remains relatively unchanged. We think it best to follow the lead of Daly (1977) in this and speak of the product of population and per capita resource use as the total impact of the human population. It is this total impact that the earth has a capacity to carry, and it is up to society to decide how to divide it between numbers of people and per capita resource use. This complicates population policy enormously, since one cannot simply state a maximum population but rather must state a maximum number of impact units. How many impact units the earth can sustain and how to distribute these impact units over the population is a dicey problem indeed, but one that must be the focus of research in this area.

Many case studies indicate that 'there is no linear relation between growing population and density, and such pressures towards land degradation and desertification' (Caldwell 1984). In fact, one study found that land degradation can occur under rising pressure of population on resources (PPR), under declining PPR and without PPR (Blaikie and Brookfield 1987). Therefore, the scientific agenda must look towards more complex, systemic models where the effects of population pressures can be analysed in their relationships with other factors. The form, structure and metabolism of cities are design variables that can be reoriented towards more comprehensive nexus goals. This would allow us to differentiate population as a 'proximate' cause of environmental degradation from the concatenation of effects of population with other factors as the 'ultimate' cause of such degradation.

Research can begin by exploring methods for more precisely estimating the total impact of population times per capita resource use. For example, the 'Ehrlich identity':

$$\begin{aligned}\text{Pollution / Area} = {} & \text{People / Area} \times \text{Economic Production /} \\ & \text{Person} \times \text{Pollution / Economic Production}\end{aligned}$$

can be operationalized as

$$\begin{aligned}\text{CO}_2\ \text{Emissions / Km}^2 = {} & \text{Population / Km}^2 \times \text{GDP /} \\ & \text{Population} \times \text{CO}_2\ \text{Emissions / GDP}\end{aligned}$$

Thus no single factor dominates the changing patterns of total impact across time. This points to the need for local studies of causal relations among specific combinations of populations, consumption and production, noting that these local studies need to aim for a general theory that will account for the great variety of local experience. Work on the 'ecological footprint' (Wackernagel and Rees 1996) has taken this approach furthest.

Another research priority is to look at the effect adding a new person has on resources, according to consumption levels and the effect that efficiency has on rising levels of consumption. Decreasing energy consumption in developed countries could dramatically decrease CO_2 emissions globally. It is only under a scenario of severe constraints on emissions in the developed countries that population growth in less developed ones plays a major global role in emission growth. If energy efficiency could be improved in the latter as well as the former, then population increase would play a much smaller role.

Research priority should also look at situations where demand (either subsistence or commercial) becomes large relative to the maximum sustainable yield of the resource, or where the regenerative capacity of the resource is relatively low, or where the incentives and restraints facing the exploiters of the resource are such as to induce them to value present gains much more highly than future gains.

Some authors single out a high rate of population growth as a root cause of environmental degradation and overload of the planet's carrying capacity. Consequently, the policy instrument is obviously population control. Ehrlich and his colleagues maintain 'There is no time to be lost in moving toward population shrinkage as rapidly as is humanly possible' (Ehrlich et al. 1989). But, as Ehrlich himself fully recognizes, the policy of focusing solely on population control is known to be insufficient. It has repeatedly been shown that it is not easily achieved in and of itself and that in addition important social and economic transformations must accompany it, such as the reduction of poverty. Even in those cases where population growth has been relatively successfully controlled, as in China, the welfare of the people has not necessarily improved and the environment is not necessarily exposed to lower rates of hazard.

The opposite position is taken by those who see high rates of population growth as stimulating economic development through inducing technological and organizational changes (Boserup 1965) or as a phenomenon that can be solved through technological change (Simon 1990).

Such positions, however, ignore the dangers of environmental depletion implicit in unchecked economic growth: consumption increases and rapidly growing populations can put a very real burden upon the resources of the earth and bring about social and political strife for control of such resources. This position also assumes that technological creativity will have the same outcomes in the future as in the past and in the South as in the North, a questionable assumption. In particular, it assumes that new technology solves old problems without creating new ones that may be even worse. Finally, it heavily discounts the importance of the loss of biodiversity—a loss that is irreversible and whose human consequences are as yet unknown.

According to a World Bank study of 64 countries, when the income of the poor rises by 1 %, general fertility rates drop by 3 % (Lappé and Schurman 1988). In contrast, other authors state that 'population is not a relevant variable' in terms of resource depletion and stress that resource consumption, particularly overconsumption by the affluent, is the key factor (Durning 1992). OECD countries represent only 18 % of the world's population and 24 % of land area, but their economies account for about 59 % of the world gross product, 78 % of road vehicles and over 50 % of global energy use. They generate about 76 % of world trade, 73 % of chemical products exports and 73 % of forest product imports and account for one-third of global GHG emissions (OECD 2011). The main policy instrument in this case, in the short term, is reducing consumption, and this can be most easily achieved in those areas where consumption per capita is highest.

With a world population that is surpassing seven billion, increasing in food and energy prices due to a lack of resources (Brown 2011), slowing of development in already underdeveloped countries due to overpopulation (Birdsall et al. 2003; Bloom and Canning 2004) and a lack of jobs (Cincotta et al. 2003), there has been a refocusing on population stability, often in the form of family-planning policies. Family planning has been proven to be very cost-effective (Singh et al. 2010): for every dollar spent on family planning, the United Nations has found that two to six dollars can be saved in the future on other development goals (UNDESA 2009). Recently the United States and the United Kingdom once again increased their foreign aid funding towards international family planning (UNDESA 2009).

An estimated one-third of global births are the result of unintended pregnancy (Bongaarts 2009). More than 200 million women in developing countries would prefer to delay their next pregnancy or not have any more children at all (Singh et al. 2003). However, several barriers prevent many of these women from making a conscious choice: lack of access to contraceptives, risk of side effects, cultural values or opposition from family members (Carr and Khan 2004; Sedgh et al. 2007).

One of the major impacts of such population growth is the negative impact it is having on the earth's life-supporting ecosystem services (Ehrlich and Ehrlich 1991; Wilson 2003; Speidel et al. 2009). It has been estimated that about half of the productivity of the earth's biosystems has been diverted to human use (Brown 2008; Jackson 2009). As population continues to increase, especially in cities, competition for these increasingly scarce resources will intensify globally. The disconnect between the 'haves' and the 'have nots' will also become more visible.

Thus a new framework should expand the definitions of issues: focus not only on population size, density, rate of increase, age distribution and sex ratios but also on access to resources, livelihoods, social dimensions of gender and structures of power. New models have to be explored in which population control is not simply a question of family planning but of economic, ecological, social and political planning, in which the wasteful use of resources is not simply a question of finding new substitutes but of reshaping affluent lifestyles and in which sustainability is seen not only as a global aggregate process but also as one having to do with sustainable livelihoods for a majority of local peoples.

To address these issues in an integrated way, we have to first better define the overall goal of the enterprise. Next we discuss sustainable human well-being as the ultimate goal and emerging research on what this means and how to achieve it.

3 Sustainable Well-Being as the Goal

Getting a better handle on how to measure the well-being and health of both ecological and economic systems, and the welfare of humans within them, is critical. This section starts with a broader definition of human well-being and how to measure it. It then looks at the conventional macroeconomic measures of welfare (gross domestic product (GDP) and related measures) and their problems as measures of well-being. It then looks at how to move beyond GDP.

3.1 Quality of Life, Happiness, Well-Being and Welfare

There is a substantial body of new research on what contributes to human well-being and quality of life. While there is still much ongoing debate, this new science clearly demonstrates the limits of conventional economic income and consumption in contributing to well-being. For example, psychologist Tim Kasser, in his 2002 book *The High Price of Materialism* (Kasser 2002), points out that people who focus on material consumption as a path to well-being are actually less satisfied with their lives and even suffer higher rates of both physical and mental illness than those who do not focus so much on material consumption. Material consumption beyond real need is a form of psychological 'junk food' that only satisfies for the moment and ultimately leads to depression, Kasser says.

Economist Richard Easterlin has shown that well-being tends to correlate well with health, level of education and marital status and shows sharply diminishing returns to income beyond a fairly low threshold. He concludes (Easterlin 2003) that:

> people make decisions assuming that more income, comfort, and positional goods will make them happier, failing to recognize that hedonic adaptation and social comparison will come into play, raise their aspirations to about the same extent as their actual gains, and leave them feeling no happier than before. As a result, most individuals spend a disproportionate amount of their lives working to make money, and sacrifice family life and health, domains in which aspirations remain fairly constant as actual circumstances change, and where the attainment of one's goals has a more lasting impact on happiness. Hence, a reallocation of time in favour of family life and health would, on average, increase individual happiness.

British economist Richard Layard synthesizes many of these ideas and concludes that current economic policies are not improving well-being and happiness and that 'happiness should become the goal of policy, and the progress of national happiness should be measured and analysed as closely as the growth of GDP [gross domestic product]' (Layard 2005).

Economist Robert Frank, in his book *Luxury Fever* (Frank 1999), also concludes that some nations would be better off—that is, overall national well-being would be higher—if we actually consumed less and spent more time with family and friends, working for our communities, maintaining our physical and mental health and enjoying nature.

On this last point, there is substantial and growing evidence that natural systems contribute heavily to human well-being. In a paper published in the journal *Nature* (Costanza et al. 1997), the annual, nonmarket value of the earth's ecosystem services was estimated to be substantially larger than global GDP. This estimate was admittedly a rough first cut, but the goal of this paper was to stimulate interest and research on the topic of natural capital and ecosystem services.

So, if we want to assess the 'real' economy—all the things that contribute to real, sustainable, human well-being—as opposed to only the 'market' economy, we have to measure and include the nonmarketed contributions to human well-being from nature; from family, friends and other social relationships at many scales; and from health and education. What does such a more comprehensive, integrative definition of well-being and quality of life look like?

3.2 The Index of Sustainable Economic Welfare and the Genuine Progress Indicator

Domestic product, whether gross or net, is not identical with true national income and that subtracting indirect business taxes from net national product (NNP), as is done in the national income accounts to arrive at 'national income', still does not give us a true measure of national income. True income is sustainable, and to calculate this Hicksian income would require a quite different approach.

We have also shown that there is a marked difference between what GDP measures and economic welfare and that the latter has been growing much more slowly than the former as measured by the two proposals that have been made for judging the US economy. A defender of the continuing use of GDP as a guide to policy could argue that, even so, economic welfare *has* advanced along with GDP. If *any* advance in the welfare measure is truly a gain, it is still desirable to increase GDP. The recognition that it takes a great deal of increase in GDP to achieve a small improvement in real economic welfare could be used to argue that ever greater efforts are needed for the increase of GDP.

To counter such a claim, two points need to be made. First, there are social and ecological indicators that are being adversely affected by growth of GDP. Not all of these are dealt with in any of the welfare measures. This is especially true of many of the pervasive externalities like the depletion of natural capital and ecosystem services (Costanza et al. 2014b).

Second, GDP interprets every expense as positive and does not distinguish welfare-enhancing activity from welfare-reducing activity (Cobb et al. 1995; Talberth et al. 2007). For example, an oil spill increases GDP because of the associated cost of cleanup and remediation, but it obviously detracts from overall well-being (Costanza et al. 2004). GDP also leaves out many components that enhance welfare but do not involve monetary transactions and therefore fall outside the market. For example, the act of picking vegetables from a garden and cooking them for family or friends is not included in GDP. Yet buying a similar meal in the frozen food aisle of the grocery store involves an exchange of money and a subsequent GDP increase. GDP also does not account for the distribution of income among individuals, which has considerable effect on individual and social well-being (Wilkinson and Pickett 2009).

A more comprehensive indicator would consolidate economic, environmental and social elements into a common framework to show net progress in well-being and quality of life (Costanza et al. 2004). A number of researchers have proposed alternatives to GDP that make one or more of these adjustments with varying components and metrics (Smith et al. 2013). Some have also noted the dangers of relying on a single indicator and have proposed a ‘dashboard’ approach with multiple indicators.

In an effort to address these issues (while remaining mindful of the pitfalls) Daly and Cobb (1989) developed an Index of Sustainable Economic Welfare (ISEW). The ISEW takes the measure of economic welfare (MEW) of Nordhaus and Tobin and the economic aspects of welfare (EAW) of Zolotas (1981) as starting points but incorporates the sustainability issues that EAW ignores and the environmental issues that MEW ignores. Rather than revising and bringing up to date the existing measures, they decided to create a new one that includes some of the elements not dealt with by any of the three indices already discussed, as well as fresh ways of treating topics that were included in them. To summarize these changes, ISEW:

1. Factors in income distribution on the assumption that an additional dollar’s worth of income adds more to the welfare of a poor family than a rich one.
2. Considerably alters what Nordhaus and Tobin (1972) did in the calculation of changes in net capital stock. Specifically, it includes only changes in the stock of fixed reproducible capital and excludes natural and human capital in this calculation.
3. Updates Zoltas’s (1981) estimates using more recent data for air and water pollution and adds an estimate of noise pollution.
4. Includes estimates of costs of the loss of wetlands and farmlands, depletion of nonrenewable resources, commuting, urbanization, auto accidents, advertising and long-term environmental damage.
5. Omits any imputation of the value of leisure.
6. Includes imputed values for the value of unpaid household labour.

Since then, the ISEW has been renamed the genuine progress indicator (GPI) (Redefining Progress 1995). Like ISEW, GPI starts with personal consumption expenditures (a major component of GDP) but adjusts it using approximately 25

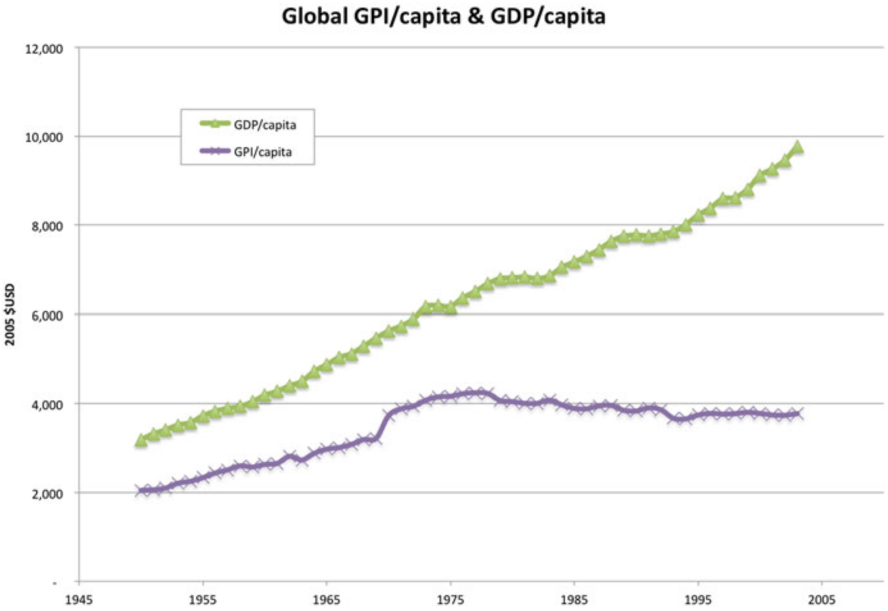

Fig. 4.1 Global GPI/capita and GDP/capita. GPI/capita was estimated by aggregating data for the 17 countries for which GPI or ISEW had been estimated and adjusting for discrepancies caused by incomplete coverage by comparison with global GDP/capita data for all countries. All estimates are in 2005 US$ (Kubiszewski et al. 2013)

different components, including income distribution, environmental costs and negative activities like crime and pollution, among others. GPI also adds positive components left out of GDP, including the benefits of volunteering and household work (Talberth et al. 2007). By separating activities that diminish welfare from those that enhance it, GPI better approximates sustainable economic welfare (Posner and Costanza 2011). GPI is not meant to be an indicator of sustainability. It is a measure of economic welfare that needs to be viewed alongside biophysical and other indicators. In the end, since one only knows if a system is sustainable after the fact, there can be no direct indicators or sustainability, only predictors (Costanza and Patten 1995).

GPI and ISEW have been calculated for various countries around the world. These studies have indicated that in many countries, beyond a certain point, GDP growth no longer correlates with increased economic welfare. A global GPI was also estimated using GPI and ISEW data from 17 countries, containing approximately 53 % of the world's population and 59 % of the global GDP (Kubiszewski et al. 2013). On the global level GPI/capita peaked in 1978 (Fig. 4.1). Interestingly, 1978 is also around the time that the human ecological footprint exceeded the earth's capacity to support humanity. Other global indicators, such as surveys of life satisfaction, also began to level off around this time.

An important function of GPI is to send up a red flag at that point (1978). Since it is made up of many benefit and cost components, it also allows for the identification of which factors increase or decrease economic welfare. Other indicators are better guides of specific aspects. For example, life satisfaction is a better measure of overall self-reported happiness. By observing the change in individual benefit and cost components, GPI reveals which factors cause economic welfare to rise or fall even if it does not always indicate what the driving forces are behind this. It can account for the underlying patterns of resource consumption, for example, but may not pick up the self-reinforcing evolution of markets or political power that drive change.

Recently, two state governments in the United States have adopted GPI as an official indicator, the states of Maryland and Vermont. In addition, the data necessary to estimate GPI is becoming more available in many countries and regions. For example, remote sensing data allow better estimates of changes in natural capital, and surveys of individuals about their time use and life satisfaction are becoming more routine. The bottom line is that the costs of estimating GPI are not particularly high, the data limitations can be overcome and it can be relatively easily estimated in most countries. Alternatively, a simplified version of GPI can also be calculated as an initial step in the process (Bleys 2007).

3.3 Towards a Measure of Total Human Welfare

While the GPI goes a long way towards providing a better measure of economic welfare, it is certainly not a perfect measure of economic welfare and it falls far short of measuring *total* welfare. GPI is still based on measuring how much is being produced and consumed, with the tacit assumption that more consumption leads to more welfare. GPI at least adjusts for the sustainability of this consumption, its negative impacts on natural capital, its distribution across income classes and other reasonable adjustments. This is a huge improvement over GDP and one that tells a very different story about recent changes in aggregate economic welfare.

A completely different approach, however, would be to look directly at the actual well-being that is achieved—to separate the means (consumption) from the ends (well-being) without assuming that one is correlated with the other. Some authors have begun to look at the problem from this perspective. For example, Manfred Max-Neef (1992) has developed a matrix of human needs and has attempted to address well-being from this alternative perspective. While human needs can be classified according to many criteria, Max-Neef organized them into two categories: existential and axiological, which he arranges as a matrix. He lists nine categories of axiological human needs which must be satisfied in order to achieve well-being: (1) subsistence, (2) protection, (3) affection, (4) understanding, (5) participation, (6) leisure, (7) creation, (8) identity and (9) freedom. These are arrayed against the existential needs of (1) having, as in consuming; (2) being, as in being a passive part of without necessarily having; (3) doing, as in actively participating in the work process; and (4) relating, as in interacting in social and organizational structures. The key idea here is that humans do not have primary needs for the products of the economy. The economy is only a means to an end. The end is the satisfaction of primary human needs. Food and shelter are ways of satisfying the need for subsistence. Insurance systems are ways to meet the need for protection. Religion is a way to meet the need for identity. Max-Neef summarizes as:

> Having established a difference between the concepts of needs and satisfiers it is possible to state two postulates: first, fundamental human needs are finite, few and classifiable; second, fundamental human needs (such as those contained in the system proposed) are the same in all cultures and in all historical periods. What changes, both over time and through cultures, is the way or the means by which the needs are satisfied (pp. 199–200).

This is a very different conceptual framework from conventional economics, which assumes that human desires are infinite and that, all else being equal, more is always better. According to this alternative conceptual framework, we should be measuring how well basic human needs are being satisfied if we want to assess well-being, not how much we are consuming, since the two are not necessarily correlated (see the earlier section that discusses subjective well-being measures).

3.4 Substitutability vs. Complementarity of Natural, Human, Social and Built Capital

The upshot of these considerations is that natural capital (natural resources) and human-made capital are complements rather than substitutes. The neoclassical assumption of near-perfect substitutability between natural resources and human-made capital is a serious distortion of reality, the excuse of 'analytical convenience' notwithstanding. To see how serious, imagine human-made capital being a perfect substitute for natural resources. Then it would also be the case that natural resources would be a perfect substitute for human-made capital. Yet if that were so, then we would have had no reason whatsoever to accumulate human-made capital since we were already endowed by nature with a perfect substitute! Historically of course we did accumulate human-made capital long before natural capital was depleted, precisely because we needed human-made capital to make effective use of the natural capital (complementarity!). It is amazing that the substitutability dogma should be held with such tenacity in the face of such an easy *reduction ad absurdum*. Add to that the fact that capital itself requires natural resources for its production—i.e. the substitute itself requires the very input being substituted for—and it is quite clear that human-made capital and natural resources are fundamentally complements, not substitutes. Substitutability of capital for resources is limited to reducing waste of materials in process, for example, collecting sawdust and using a press (capital) to make particleboard. And no amount of substitution of capital for resources can ever reduce the mass of material resource inputs below the mass of the outputs, given the law of conservation of matter–energy.

Substitutability of capital for resources in aggregate production functions reflects largely a change in the total product mix from resource-intensive to different capital-intensive products. It is an artefact of product aggregation, not factor substitution (i.e. along a given product isoquant). It is important to emphasize that it is this latter meaning of substitution that is under attack here—producing a given physical product with less natural resources and more capital. No one denies that it is possible to produce a different product or a different product mix with fewer resources. Indeed new products may be designed to provide the same or better service while using fewer resources and sometimes less labour and less capital as well. This is a technical improvement, not a substitution of capital for resources. Light bulbs that give more lumens per watt represent technical progress and qualitative improvement in the state of the art, not the substitution of a quantity of capital for a quantity of natural resource in the production of a given quantity of a product. In addition, increases in efficiency can sometimes lead to increases in consumption if they free up financial resources that can be spent of other consumption items. Saving money on petrol for your hybrid Prius would allow you to buy more consumption items that may, in fact, consume more resources than the petrol you saved.

It may be that economists are speaking loosely and metaphorically when they claim that capital is a near-perfect substitute for natural resources. Perhaps they are counting as ‘capital’ all improvements in knowledge, technology, managerial skill and so on—in short anything that would increase the efficiency with which resources are used. If this is the usage, then ‘capital’ and resources would by definition be substitutes in the same sense that more efficient use of a resource is a substitute for using more of the resource. But to define capital as efficiency would make a mockery of the neoclassical theory of production, where efficiency is a ratio of output to input and capital is a quantity of input.

The productivity of human-made capital is more and more limited by the decreasing supply of complementary natural capital. Of course in the past when the scale of the human presence in the biosphere was low, human-made capital played the limiting role. The switch from human-made to natural capital as the limiting factor is thus a function of the increasing scale of the human presence.

3.5 Growth vs. Development

Improvement in human welfare can come about by pushing more matter–energy through the economy (i.e. increases in scale) or by squeezing more human want satisfaction out of each unit of matter–energy that passes through. These two processes are so different in their effect on the environment that we must stop conflating them. It is better to refer to throughput increase as *growth* and efficiency increase as *development.* Growth is destructive of natural capital and beyond some point will cost us more than it is worth—that is, sacrificed natural capital will be worth more than the extra human-made capital whose production necessitated the sacrifice. At this point growth has become antieconomic, impoverishing rather than enriching.

Development, or qualitative improvement, is not at the expense of natural capital. There are clear economic limits to growth, but not to development. This is not to assert that there are no limits to development, only that they are not so clear as the limits to growth, and consequently there is room for a wide range of opinion on how far we can go in increasing human welfare without increasing resource throughput. How far can development substitute for growth? This is the relevant question, not how far can human-made capital substitute for natural capital, the answer to which, as we have seen, is 'hardly at all'.

Still, great uncertainty and debate exists as to whether economic growth promotes overall well-being. This uncertainty is critical since economic growth policies, also known as neoliberal policies, are being disseminated to all developing countries around the world. The promotion of economic growth is based on the assumption that increases in wealth and material consumption lead to increases in well-being (Samuelson 1947; Easterlin 1995; Oswald 1997; Goklany 2002; Layard 2005; Kusago 2007).

After 20 years of implementing neoliberal policies, many countries have experienced economic growth (Edwards 1992; Amann and Baer 2002) as well as decreases in poverty levels in certain countries (Lodoño and Skékely 2000) and increases in well-being through improvements in living standards, as measured by GDP, life expectancy and decreases in child mortality (Krueger 1997; Goklany 2002).

However, these neoliberal policies have also brought about high economic, social and environmental costs, often outweighing the improvements in well-being. Chile, often considered as the perfect model of neoliberal growth, has experienced several negative effects due to these policies (Green 1996; Schurman 1996; Altieri and Rojas 1999; Baer and Maloney 2003; Homedes and Ugalde 2005). In recent years, economic growth has either declined or become stagnant in many developing nations (Muradian and Martinez-Alier 2001; Mahon 2003; Held 2005). Subjective well-being has decreased in many developed countries such as the United States, Japan and most countries in Europe, as well as most recently in China (Oswald 1997; Layard 2003; Kahneman and Krueger 2006). The inequality gap within and between countries continues to increase (Lodoño and Skékely 2000; Muradian and Martinez-Alier 2001; Wade 2004; Navarro 2007). Poverty is still a major problem in many countries around the world, and there is controversy regarding the magnitude of the poverty reduction that has occurred (Lodoño and Skékely 2000; Wade 2004; Held 2005). Also, increased dependency on degrading (especially primary) natural resources has exacerbated environmental pressures and increased the rate of species extinction (Kessler and Van Dorp 1998; Muradian and Martinez-Alier 2001; Paus et al. 2003; McCarthy and Prudham 2004).

Some people believe that there are truly enormous possibilities for development without growth. Energy efficiency, they argue, can be vastly increased (Lovins and Lovins 1987; Lovins 1997), likewise the efficiency of water use. Other materials are not so clear. Others (Costanza 1980; Cleveland et al. 1984; Gever et al. 1986; Hall et al. 1986) believe that the bond between growth and energy use is not so loose. This issue arises in the Brundtland Commission's Report (World Commission on Environment and Development 1987) where on the one hand there is a recognition that the scale of the human economy is already unsustainable in the sense that it requires the consumption of natural capital and yet on the other hand there is a call for further economic expansion by a factor of 5 to 10 in order to improve the lot of the poor without having to appeal too much to the 'politically impossible' alternatives of serious population control and redistribution of wealth. The big question is: how much of this called for expansion can come from development and how much must come from growth? This question is not addressed by the commission. But statements from the secretary of the World Commission on Environment and Development (WCED), Jim MacNeil (1990), that 'The link between growth and its impact on the environment has also been severed' (p. 13) and 'the maxim for sustainable development is not 'limits to growth'; it is "the growth of limits"' indicate that WCED expects the lion's share of that factor of 5–10 to come from development, not growth. They confusingly use the word 'growth' to refer to both cases, saying that future growth must be qualitatively very different from past growth. When things are qualitatively different, it is best to call them by different names, hence our distinction between growth and development. Our own view is that WCED is too optimistic—that a factor of 5–10 increase cannot come from development alone and that if it comes mainly from growth, it will be devastatingly unsustainable. Therefore, the welfare of the poor, and indeed of the rich as well, depends much more on population control, consumption control and redistribution than on the technical fix of a five- to tenfold increase in total factor productivity.

We acknowledge, however, that there is a vast uncertainty on this critical issue of the scope for economic development from increasing efficiency. We have therefore devised a policy that should be sustainable regardless of who is right in this debate. The basic logic is simple: protect the pessimists against their worst fears and encourage the optimists to pursue their dreams by the same policy, namely, limit throughput.

4 Natural Capital

We have briefly defined the four types of capital assets that are necessary to support human well-being in a sustainable and desirable way. We have pointed out that these four types of capital are, in general, compliments rather than substitutes and that we need to differentiate between *growth* in the scale of the built and human capital components of the system and *development* of the quality of interactions between all four types of capital. Next we go into more detail about natural capital and its importance to both conventional marketed economic production and to the supply of nonmarketed ecosystem services.

One major issue is the relation between natural capital, which yields a flow of natural resources and services that enter the process of production, and the human-made capital that serves as an agent in the process for transforming the resource inflow into a product outflow. Is the flow of natural resources (and the stock of natural capital that yields that flow) substitutable by human-made capital?

Clearly one resource can substitute for another—we can transform aluminium instead of copper into electric wire. We can also substitute labour for capital, or capital for labour, to a significant degree even though the characteristic of complementarity is also important. For example, we can have fewer carpenters and more power saws or fewer power saws and more carpenters and still build the same house. In other words one resource can substitute for another, albeit imperfectly, because both play the same qualitative role in the production: both are raw materials undergoing transformation into a product. Likewise capital and labour are substitutable to a significant degree because both play the role of agent of transformation of resource inputs into product outputs. However, when we come to substitution across the roles of transforming agent and material undergoing transformation (efficient cause and material cause), the possibilities of substitution become very limited and the characteristic of complementarity is dominant. For example, we cannot make the same house with half the lumber no matter how many extra power saws or carpenters we try to substitute. Of course we might substitute brick for lumber, but then we face the analogous limitation—we cannot substitute masons and trowels for bricks.

We may define capital broadly as a stock of something that yields a flow of useful goods or services. Traditionally capital was defined as produced means of production, which we call here human-made capital, as distinct from natural capital which, though not made by humans, is nevertheless functionally a stock that yields a flow of useful goods and services. We can distinguish renewable from nonrenewable natural capital and marketed from nonmarketed natural capital, giving four cross-categories. Natural capital consists of physical stocks that are complementary to human-made capital. We have learned to use the concept of human capital (i.e. skills, education, etc.), which departs even more fundamentally from the standard definition of capital. Human capital cannot be bought and sold, although it can be rented. Although it can be accumulated, it cannot be inherited without effort by bequest as can ordinary human-made capital but must be relearned anew by each generation. Natural capital, however, is more like traditional human-made capital in that it can be bequeathed. Overall the concept of natural capital is less a departure from the traditional definition of capital than is the commonly used notion of human capital.

There is a large subcategory of marketed natural capital that is intermediate between natural and human-made, which we might refer to as ‘cultivated natural capital’. This consists of such things as plantation forests, herds of livestock, agricultural crops, fish bred in ponds and so on. Cultivated natural capital supplies the raw material input complementary to human-made capital, but does not provide the wide range of natural ecological services characteristic of natural capital proper (e.g. eucalyptus plantations supply timber to the sawmill and may even reduce erosion, but do not provide a wildlife habitat or conserve biodiversity). Investment in the cultivated natural capital of a plantation forest, however, is useful not only for the lumber, but as a way of easing the pressure of lumber interests on the remaining true natural capital of natural forests.

Marketed natural capital can, subject to the important social corrections for common property and myopic discounting, be left to the market. Nonmarketed natural capital, both renewable and nonrenewable, will be the most troublesome category. Remaining natural forests should in many cases be treated as nonmarketed natural capital and only replanted areas treated as marketed natural capital.

4.1 Natural Capital and Ecosystem Services

Ecological systems play a fundamental role in supporting life on earth at all hierarchical scales. They form the life-support system without which economic activity would not be possible. They are essential in global material cycles like the carbon and water cycles. Ecosystems produce renewable resources and services. For example, a fish in the sea is produced by several other 'ecological sectors' in the food web of the sea. The fish is a part of the ecological system in which it is produced, and the interactions that produce and sustain the fish are inherently complex.

Ecosystem services are the ecological characteristics, functions or processes that directly or indirectly contribute to human well-being—the benefits people derive from functioning ecosystems (Costanza et al. 1997; Millennium Ecosystem Assessment (MEA) 2005). Ecosystem processes and functions may contribute to ecosystem services but they are not synonymous. Ecosystem processes and functions describe biophysical relationships and exist regardless of whether or not humans benefit (Granek et al. 2010). Ecosystem services, on the other hand, only exist if they contribute to human well-being and cannot be defined independently.

The following categorization of ecosystem services has been used by the Millennium Ecosystem Assessment (2005):

(a) *Provisioning services*—ecosystem services that combine with built, human and social capital to produce food, timber, fibre or other 'provisioning' benefits. For example, fish delivered to people as food require fishing boats (built capital), fisherfolk (human capital) and fishing communities (social capital) to produce.
(b) *Regulating services*—services that regulate different aspects of the integrated system. These are services that combine with the other three capitals to produce flood control, storm protection, water regulation, human disease regulation, water purification, air quality maintenance, pollination, pest control and climate control. For example, storm protection by coastal wetlands requires built infrastructure, people and communities to be protected. These services are generally not marketed but have clear value to society.
(c) *Cultural services*—ecosystem services that combine with built, human and social capital to produce recreation, aesthetic, scientific, cultural identity, sense of place or other 'cultural' benefits. For example, to produce a recreational benefit requires a beautiful natural asset (a lake), in combination with built infrastructure (a road, trail, dock, etc.), human capital (people able to appreciate the lake experience) and social capital (family, friends and institutions that

make the lake accessible and safe). Even 'existence' and other 'non-use' values require people (human capital) and their cultures (social and built capital) to appreciate.

(d) *Supporting services*—services that maintain basic ecosystem processes and functions such as soil formation, primary productivity, biogeochemistry and provisioning of habitat. These services affect human well-being *indirectly* by maintaining processes necessary for provisioning, regulating and cultural services. They also refer to the ecosystem services that have not yet or may never be intentionally combined with built, human and social capital to produce human benefits but that support or underlie these benefits and may sometimes be used as proxies for benefits when the benefits cannot be easily measured directly. For example, net primary production (NPP) is an ecosystem function that supports carbon sequestration and removal from the atmosphere, which combines with built, human and social capital to provide the benefit of climate regulation. Some would argue that these 'supporting' services should rightly be defined as ecosystem 'functions', since they may not yet have interacted with the other three forms of capital to create benefits. We agree with this in principle, but recognize that supporting services/functions may sometimes be used as proxies for services in the other categories.

This categorization suggests a very broad definition of services, limited only by the requirement of a contribution to human well-being. Even without any subsequent valuation, explicitly listing the services derived from an ecosystem can help ensure appropriate recognition of the full range of potential impacts of a given policy option. This can help make the analysis of ecological systems more transparent and can help inform decision makers of the relative merits of different options before them (Costanza et al. 2011).

Examples of these services include the maintenance of the composition of the atmosphere, amelioration and stability of climate, flood controls and drinking water supply, waste assimilation, recycling of nutrients, generation of soils, pollination of crops, provision of food, maintenance of species and a vast genetic library and also maintenance of the scenery of the landscape, recreational sites and aesthetic and amenity values (Ehrlich and Mooney 1983; Folke 1991; de Groot 1992; Ehrlich and Ehrlich 1992; Costanza et al. 1997, 2014b; de Groot et al. 2002). Biodiversity at genetic, species, population and ecosystem levels all contribute in maintaining these functions and services (Worm et al. 2006). Cairns and Pratt (Cairns and Pratt 1995) argue that a highly environmentally literate society would probably accept the assertion that most, if not all ecosystem functions, are in the long term beneficial to society.

Many ecosystem services are public goods. This means they are non-excludable and multiple users can simultaneously benefit from using them. This creates circumstances where individual choices are not the most appropriate approach to valuation. Instead, some form of community or group choice process is needed. Furthermore, ecosystem services (being public goods) are generally not traded in markets. We therefore need to develop other methods to assess their value.

There are a number of methods that can be used to estimate or measure benefits from ecosystems. Valuation can be expressed in multiple ways, including monetary units, physical units or indices. Economists have developed a number of valuation methods that typically use metrics expressed in monetary units (Freeman 2003), while ecologists and others have developed measures or indices expressed in a variety of nonmonetary units such as biophysical trade-offs (Costanza 2004).

The study of ecosystem services has grown exponentially in the past few decades as seen through the publication records (Costanza and Kubiszewski 2012). The most influential of these studies was published in 1997 by Costanza and colleagues, which estimated global monetary value of ecosystems in a *Nature* article entitled 'The value of the world's ecosystem services and natural capital' (Costanza et al. 1997). This paper estimated the value of 17 ecosystem services for 16 biomes to be in the range of US$16–54 trillion per year, with an average of US$33 trillion per year, a figure larger than annual GDP at the time. This area of publication has grown exponentially. In this study, estimates of global ecosystem services were derived from a synthesis of previous studies that utilized a wide variety of techniques like those mentioned above to value-specific ecosystem services in specific biomes. This technique, called 'benefit transfer', uses studies that have been done at other locations or in different contexts, but can be applied with some modification. Such a methodology, although useful as an initial estimate, is just a first cut and much progress has been made since then (USEPA Science Advisory Board 2009).

More recently, with the publication of the Millennium Ecosystem Assessment (MEA), the concept of ecosystem services gained the attention of a broader academic audience and the public (Millennium Ecosystem Assessment (MEA) 2005). The MEA was a 4-year, 1300 scientist study commissioned by the United Nations in 2005. The report analysed the state of the world's ecosystems and provided recommendations for policymakers. It determined that human actions have depleted the world's natural capital to the point that the ability of a majority of the globe's ecosystems to sustain future generations can no longer be taken for granted.

In 2008, a second international study was published on The Economics of Ecosystems and Biodiversity (TEEB), hosted by United Nations Environment Programme (UNEP). TEEB's primary purpose was to draw attention to the global economic benefits of biodiversity, to highlight the growing costs of biodiversity loss and ecosystem degradation and to draw together expertise from the fields of science, economics and policy to enable practical actions moving forward. The TEEB report was picked up extensively by the mass media, bringing ecosystem services to a broad audience.

With such high-profile reports being published, ecosystem services have entered not only the public media (Schwartz 2010) but also into business. Dow Chemical recently established a $10 million collaboration with The Nature Conservancy to tally up the ecosystem costs and benefits of every business decision (Walsh 2011). Such collaboration will provide a significant addition to ecosystem services valuation knowledge and techniques. However, there is significant research that is still required.

Hundreds of projects and groups are currently working towards better understanding, modelling, valuation and management of ecosystem services and natural capital. It would be impossible to list all of them here, but the new Ecosystem Services Partnership (ESP, http://www.es-partnership.org/) is global network that does just that and helps to coordinate the activity and build consensus.

5 An Integrated, Nexus Approach to Urban Design and Planning

How does all this relate to urban design and planning? It means that we have to take a much more integrated, whole systems approach to this problem. Failure to do this has lead to poorly designed, poorly functioning, unsustainable and undesirable urban systems. The neglect of an integrated approach and the current compartmentalization of the different components of planning for urban systems, combined with the disconnect in planning between urban systems and their rural and global hinterlands means that important connections and feedback mechanisms remain invisible.

There are, of course, good examples of cities that have incorporated an integrated approach and these are models that can be built upon. Portland, Oregon, is one well-known example, where the functions of planning and sustainability are integrated in one office, urban growth boundaries have been in effect since the 1970s and social capital, natural capital and ecosystem services are terms that can be heard in everyday conversation.

There is no simple answer to how to achieve a nexus approach to urban and regional planning, but we believe that a critical first step is to develop a shared vision of the goal for the system. Scenario planning incorporating the four-capital model of ecological economics is one way to do this. In addition we can employ the latest in Internet communication and crowd sourcing to build, evaluate and communicate scenarios.

5.1 Scenario Planning and Modelling with the Four-Capital Model

'Scenario' is a term with multiple meanings. Scenario exercises vary in their objectives and hence their characteristics (Biggs et al. 2007), and we acknowledge that each of the many variants has an important place in decision-making processes. In this case, we define scenario analysis or scenario planning as a structured process of exploring and evaluating the future. Scenarios consider how alternative futures, typically structured around the identification of a focal issue (O'Brien 2000), may unfold from combinations of the most influential and uncertain drivers and their interactions with more certain driving forces.

Scenario planning differs from forecasting, projections and predictions, in that it explores plausible rather than probable futures (Peterson et al. 2003). Scenarios are most useful for dealing with uncertainty when there is insufficient information about the probabilities that different events will occur. Scenario planning is based on four assumptions (DTI 2003):

1. The future is unlike the past and is significantly shaped by human choice and action
2. The future cannot be foreseen, but exploring possible futures can inform present decisions
3. There are many possible futures; scenarios therefore map within a 'possibility space'
4. Scenario development involves both rational analysis and creative thinking

Scenarios are best suited to exploring situations of high uncertainty and low controllability (Peterson et al. 2003), for example, climate change and global governance. In these situations, scenarios can help to illuminate the consequences of these uncontrollable forces and to formulate robust responses locally. A frequently cited example is the use of scenarios by Royal Dutch Shell (Wack 1985; Kahane 1992). Shell began developing scenarios in the 1970s and engaged in a process to imagine a future that, at the time, no one thought would happen. When turbulence hit the world oil market in the late 1970s, Shell, though unable to directly intervene in the market, navigated the shocks much better than its competitors who did not use scenarios for strategic planning.

Although aspects of the future worlds depicted by scenarios may come to eventuate in time, these worlds are best treated as caricatures of reality from which we can learn. Often, they illustrate alternative 'stable states' or 'basins of attraction' that can be either desirable or undesirable worlds to live in. The ultimate role of scenarios is to help understand how society can either exit an undesirable world or make it more desirable (Gallopin 2002).

Scenarios have been developed for a range of applications from global to local scales, including corporate strategy (Wack 1985), political negotiations (Kahane 1992; Kahane 2004) and community-based natural resource management (Wollenberg et al. 2000; Evans et al. 2006; Bohensky et al. 2011).

How could scenario planning be applied to integrated urban planning? Representatives of major stakeholder groups can come together to envision plausible futures for these areas. These scenarios would cover the full range of options, from business-as-usual development to more sustainable futures. In all cases the scenarios must be 'plausible'—meaning that they should take scientific evidence into account and combine rational analysis and creative thinking.

Scenario planning has been shown to work, even in very contentious situations, by bringing together stakeholders to think together about options for the whole system (Kahane 2004). It allows participants to step out of their special interest mode and begin to build shared visions. Scenario planning is now embedded in the strategic thinking of some of the world's most influential institutions, including the World Bank and United Nations Environment Programme. Scenario planning was used in the Millennium Ecosystem Assessment to chart possible trajectories for the global community based on the rate and extent of ecological change and the interactions with management policies (Carpenter 2005). Scenario planning need not be static; scenarios can be revisited and reworked as part of a long-term formal process, for example, the application of scenario planning to guide water management in the Netherlands from the 1950s (Haasnoot and Middelkoop 2012).

Once a range of scenarios is created, a consensus often emerges among participants as to which options are most desirable and risk averse, given underlying uncertainties about the future. For example, in South Africa a scenario planning process involving all political parties developed four scenarios for the country's transition out of apartheid (Kahane 2004). The 'flight of the flamingos' scenario that envisioned both black and white South Africans rising up together emerged as the clear consensus and lead to the truth and reconciliation and other strategies that allowed a relatively peaceful and cooperative transition in a situation that might have otherwise become quite violent and repressive. The development of an evidence-based understanding of how the world works, combined with a shared vision of how we want it to work, are powerful tools to tackle even the most complex and recalcitrant of problems.

To take the process of empowerment to its logical conclusion, we recommend that scenarios be put to the public in the form of opinion surveys (Costanza 2000; Costanza et al. 2015). As far as we are aware, such sampling of public opinion about scenarios has been very limited. An instructive example is provided, however, by the designers of an online scenario game for exploring futures in New Zealand (Landcare Research Scenarios Working Group 2007). Several hundred game participants provided telling feedback on the scenario space they considered New Zealand to be in now, where they would like the country to be in 50 years and where they thought New Zealand was actually heading. While the overwhelming majority of respondents sought a future characterized by greater environmental sustainability and social cohesion, they considered that the country was heading in the opposite direction.

5.2 The Potential for Computer Games and Crowd Sourcing

Games have been popular throughout human history to educate and entertain. Even the simplest of games can be thought of as simulations of some aspect of life. Some of these simulations can be quite complex and useful. Examples include war games and flight simulators. Games that can be used for research to understand some aspect of human behaviour have also become quite popular and useful. For example, von Neumann and Morgenstern (Von Neumann and Morgenstern 1953) formulated much of economic behaviour around 'games of strategy'. More recently, the Prisoner's Dilemma game has been used extensively to understand the evolution of cooperative behaviour. A search of the ISI Web of Knowledge for the topic ‘Prisoner’s Dilemma’ turned up over 1,700 papers. The most frequently cited of these was the 1981 article by Axelrod and Hamilton (1981). In 2002, Vernon Smith was awarded the Nobel Prize in economics for his pioneering role in the development of experimental economics, which, in essence, uses simple games to test behavioural responses to different value propositions.

Rapidly advancing technology has provided the increasing ability to bring realistic detail to recreational computer games. Imagine such a game that also offers academically rigorous, peer-reviewed representations of earth’s attributes including human interactions. Millions of players could test and provide solutions to problems that challenge policy analysts, corporate executives, climate scientists, philanthropists, economists, government leaders, sociologists and scenario planners.

The promise of games that integrate research, education and entertainment is huge, but has rarely been achieved. One of the few examples is the ‘World Game’ first developed in 1961 by R. Buckminster Fuller, originally as a global simulation alternative to war games. The World Game allows a group of players to cooperatively develop a set of global scenarios. The goal is to ‘make the world work for 100% of humanity in the shortest possible time through spontaneous cooperation without ecological damage or disadvantage to anyone’, thus increasing the quality of life for all people. The World Game has been played by thousands of people, with and without the aid of computers over the years. It is now offered by *osearth.com* as a global simulation game for 40–600 players in educational workshops. Another recent example is an extension to a very popular board game ‘Settlers of Catan’ called ‘Catan: Oil Springs’ (Griswold 2013) that incorporates oil resource depletion into the game.

We now have the capability to link relatively sophisticated computer simulations with engaging game interfaces over the Internet, allowing us to observe and record player behaviour. Harvesting such information—or crowd sourcing—from games may help answer both basic and complex research questions, while at the same time entertaining and educating game players. In this paper we outline a novel approach for integrating research, educational and entertainment outcomes within a gaming environment, focusing on and facilitating exploration of the valuation of ecosystem services—that is, on those processes and functions of ecosystems that benefit human society. To date, while some popular games broadly explore aspects of the nexus approach advocated here, or could be modified to do so (e.g. SimCity, Civilization, Myst), there is a huge opportunity to better integrate such interfaces with research and public participation in the urban and regional design process. This could allow a huge increase in public engagement in the design and planning process that could incorporate the ecological economics framework we have discussed.

6 Conclusions and Recommendations

Ecological economics and the four-capital model provide a framework for an integrated, nexus approach to urban and regional planning. It is based on a reformulation of the central goal as a high and sustainable quality of life that is equitably shared. Our current socioecological regime and its set of interconnected worldviews, institutions and technologies all support the vision of unlimited growth of material production and consumption as a proxy for quality of life. However, abundant evidence shows that, beyond a certain threshold, further material growth only marginally contributes to improvement in quality of life. Not only does further material growth not meet humanity's central goal, there is mounting evidence that it creates significant roadblocks to sustainability through increasing resource constraints (i.e. peak oil, water limitations), sink constraints (i.e. climate disruption, biodiversity loss, pollution) and the inequitable distribution of wealth. Overcoming these roadblocks and creating a sustainable and desirable future will require an integrated, systems-level redesign of our cities and our entire socioecological regime and economic paradigm focused explicitly and directly on the goal of sustainable quality of life and well-being with minimal waste rather than the proxy of unlimited material growth. It will require the recognition and measurement of the contributions of natural and social capital to sustainable well-being. It is a design problem on a massive scale. This transition, like all cultural transitions, will occur through an evolutionary process, but one that we, to a certain extent, can control and direct through the process of shared envisioning and the creation of both physical and computer models. Visions and models of integrated sets of worldviews, institutions and technologies are needed to stimulate and seed this evolutionary redesign.

To make the transition to a just and sustainable world will require:

1. A fundamental change of worldview to one that recognizes that we live on a finite planet and that sustainable well-being requires far more than material consumption
2. Replacing the present goal of limitless growth with goals of material sufficiency, equitable distribution and sustainable human well-being
3. A complete redesign of the world economy that preserves natural systems essential to life and well-being and balances natural, social, human and built assets

The dimensions of the new system include, but are not limited to, the following:

Sustainable scale: respecting ecological limits:

- Establishment of systems for effective and equitable governance and management of the natural commons, including the atmosphere, oceans and biodiversity

- Creation of cap-and-auction systems for basic resources, including quotas on depletion, pollution and greenhouse gas emissions, based on basic planetary boundaries and resource limits
- Consuming essential nonrenewables, such as fossil fuels, no faster than we develop renewable substitutes
- Investments in sustainable infrastructure, such as renewable energy, energy efficiency, public transit, watershed protection measures, green public spaces and clean technology
- Dismantling incentives towards materialistic consumption, including banning advertising to children and regulating the commercial media
- Linked policies to address population and consumption

Fair distribution: protecting capabilities for flourishing:

- Sharing the work to create more fulfilling employment and more balanced leisure–income trade-offs
- Reducing systemic inequalities, both internationally and within nations, by improving the living standards of the poor, limiting excess and unearned income and consumption and preventing private capture of common wealth
- Establishment of a system for effective and equitable governance and management of the social commons, including cultural inheritance, financial systems and information systems like the Internet and airwaves

Efficient allocation: building a sustainable macroeconomy:

- Use of full-cost accounting measures to internalize externalities, value nonmarket assets and services, reform national accounting systems and ensure that prices reflect actual social and environmental costs of production
- Fiscal reforms that reward sustainable and well-being-enhancing actions and penalize unsustainable behaviours that diminish collective well-being, including ecological tax reforms with compensating mechanisms that prevent additional burdens on low-income groups
- Systems of cooperative investment in stewardship (CIS) and payment for ecosystem services (PES)
- Increased financial and fiscal prudence, including greater public control of the money supply and its benefits and other financial instruments and practices that contribute to the public good
- Ensuring availability of all information required to move to a sustainable economy that enhances well-being through public investment in research and development and reform of the ownership structure of copyrights and patents

An integrated nexus approach to urban and regional planning and design based on an ecological economics framework can be a central component of this transition to a sustainable and desirable future.

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Chapter 5
The Urban Water–Energy Nexus: Building Resilience for Global Change in the "Urban Century"

Christopher A. Scott, Arica Crootof, and Sarah Kelly-Richards

Abstract

- The urban water–energy nexus is defined as the interlinkages among water, energy, and attendant infrastructure, coupled with the populations that rely on them and the institutions for their governance. Because these interlinkages shape the future trajectory of cities – their form, function, and footprint – the nexus can be harnessed as a holistic policy tool to incorporate a holistic approach to build societal and ecosystem resilience to global change.
- Resource attributes of water and energy along with the large infrastructure systems conventionally used to source, transport, and distribute them, plus recover waste, make water and energy the core resources to consider for urban planning in a nexus framework.
- Urbanization drives the nexus in unique ways due to (a) political/economic power and demographic concentration in cities, (b) reliance on infrastructure, (c) global change forces, and (d) unique urban social vulnerabilities.
- In the face of multiple global change uncertainties, cities are experiencing increasing pressures as a result of climate change and economic globalization. Resilience provides a guiding principle for multi-scalar urban planning and management to increase urban adaptive capacity.
- Research gaps and next steps in urban water–energy nexus research and practice are centered on more robust analysis of waste and resource recovery, including the opportunities and limits to efficiency gains.

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H. Hettiarachchi, R. Ardakanian (eds.), *Environmental Resource Management and the Nexus Approach*, DOI 10.1007/978-3-319-28593-1_5

Key Points

This chapter defines a unique *urban water–energy nexus* and discusses policy and planning following resilience principles. In form and content, the chapter addresses the following key points:

- *The urban water–energy nexus is defined as the interlinkages among water, energy, and attendant infrastructure, coupled with the populations that rely on them and the institutions for their governance. Because these interlinkages shape the future trajectory of cities – their form, function, and footprint – the nexus can be harnessed as a holistic policy tool to incorporate a holistic approach to build societal and ecosystem resilience to global change.*
- Resource attributes of water and energy along with the large infrastructure systems conventionally used to source, transport, and distribute them, plus recover waste, make water and energy the core resources to consider for urban planning in a nexus framework.
- Urbanization drives the nexus in unique ways due to (a) political/economic power and demographic concentration in cities, (b) reliance on infrastructure, (c) global change forces, and (d) unique urban social vulnerabilities. We draw on social–ecological systems and urban metabolism theoretical approaches to advance scholarship on the urban water–energy nexus.
- In the face of multiple global change uncertainties, cities are experiencing increasing pressures as a result of climate change and economic globalization. Resilience provides a guiding principle for multi-scalar urban planning and management to increase urban adaptive capacity. This principle emphasizes the evolutionary nature of urbanization, manifold social and ecological connections in the urban sphere, and the ability of systems to quickly recover from crisis.
- Five case studies demonstrate the coupled relationships between urban water and energy and offer important lessons for the Sustainable Development Goals (SDGs).
- Research gaps and next steps in urban water–energy nexus research and practice are centered on more robust analysis of waste and resource recovery, including the opportunities and limits to efficiency gains.

1 Introduction

Global change exerts pressures on the social, ecological, and technological dimensions of cities. In this chapter, we outline planning principles for resilient cities through the urban water–energy nexus framework to confront these increasing pressures. Urbanization poses challenges and opportunities for resource use and institutional dimensions of global change. Increased population growth, primarily in urban environments, can lead to increased stress on water and energy resources; however there are opportunities for integrative water and energy policy and management that adapt and respond to urbanization. Considering that most twenty-first-century population growth is occurring in cities, in a time of increasing climatic change, innovative policy and practice are needed to meet these changing conditions. We follow Ester Boserup's approach that expanding human populations, provided capacity and flexibility to unleash creativity, hold immense promise for innovation and adaptation and therefore constitute a potent source of positive change.

Multiple processes and scales of interlinkage between society and the environment drive global change, on the one hand, and yet offer opportunities for sustainable transitions, on the other. Thus, our view is one of human–environment coevolution: the complex dynamics of the resource nexus, that is, the interrelation of environmental resources such as water, energy, and food, which cannot be managed separately in practice, are shaped by intricate societal and economic processes, which in turn act upon and are deeply influenced by resource use and access, and environmental quality more generally.

Climate change is an important determinant of the availability and demand for water as well as a central factor in energy demand and the technology choices for energy generation. Our analysis views climate change in contextual terms, i.e., how urbanization drives resource provisioning of water, energy, and food and the institutions linked to these, within broader processes of global warming, sea level rise, changing rainfall, and extreme events (especially flooding). Urban adaptation to these and other processes of climate change must increasingly rely on an integrated nexus-based understanding of water and energy management (Nair et al. 2014; Birkmann et al. 2010).

This chapter focuses explicitly on the urbanization drivers and responses to global change. Global change is framed in terms of planetary-scale climate dynamics, global and regional market processes, and environmental governance and policy initiatives. This chapter explores what makes the urban water–energy nexus unique by focusing on infrastructure, institutions (understood as North's "rules of the game"), and urban–rural gradients in relation to megacities (Kraas 2007; Varis et al. 2006), regional cities, and urbanizing towns (Young and Keil 2010; Swyngedouw 2004). The nexus framework provides the ability to compare across diverse settings; however we emphasize the importance of context-specific management and policy decisions. These resource and institutional nexus dynamics are connected to broader networks of resource flows and to human migration and population growth that drive urbanization at the global scale.

The urban water–energy nexus is defined as the interlinkages among water, energy, and attendant infrastructure, coupled with the populations that rely on them and the institutions for their governance. Because these interlinkages shape the future trajectory of cities – their form, function, and footprint – the nexus can be harnessed as a holistic policy tool to incorporate a holistic approach to build societal and ecosystem resilience to global change. The urban water–energy nexus embodies resource consumption, production, and management tied with social dynamics such as the unequal distribution of wealth, access, and decision-making power. Thus it requires considering social equity, resource access, and political power (the societal components of the water–energy nexus). Transformations in resource availability and quality are just as much a result of their development, access, and control as they are questions merely of physical endowment, i.e., location and abundance of resources. Because the interlinkages among water, energy, and infrastructure are dynamic, the nexus influences emergent societal properties. This heightens the political dimensions of the nexus, as Williams et al. (2014) state: “The contested relationships, processes and technologies through which energy and water become enrolled in nexus interactions – what we might call the political production of the nexus – are drastically overlooked in existing scholarship.”

This chapter is organized as follows: We discuss how to integrate the urban water–energy nexus into policy. We do so by reviewing social–ecological system resilience, urban metabolism, and nexus-based understandings of global change. Next, we review five case studies that illustrate different dimensions of the urban water–energy nexus. We go on to discuss nexus-informed planning, outlining opportunities and limitations for adaptation, mitigation, and resilience in the face of climate change in the urban sphere. In the discussion, we inform the debate on the Sustainable Development Goals in relation to the urban water–energy nexus. The conclusions address future directions for nexus research, practice, and policy.

2 Integrating the Urban Water–Energy Nexus into Policy

2.1 Social–Ecological System (SES) Resilience

The coevolutionary understanding of human–environment interactions that underpins our conceptual contributions to policymaking has gained increased recognition in several schools of thought, including ecological economics, political ecology, social–ecological systems, and societal and ecosystem metabolism. All four of these intellectual traditions in some fashion view the human use of resources as influencing environmental conditions, while, in turn, the changing environment is seen to alter social relations. Thus, all consider the coupled nature of society and ecosystems in dynamic, iterative terms. Each approach places a different emphasis on the locus, attribution, and drivers of change. We focus here on SES for its theoretical grounding in, and continuing development and claims to intellectual ownership of, *resilience*, understood as the ability of coupled systems to undergo periodic, often abrupt change, while still retaining essential function (Walker and Salt 2012). As discussed by Costanza (2012), resilience can also be defined as the ratio between the stress threshold of the system, or the maximum stress it can withstand, divided by the time required to recover from the stress. Our main objective is not to further theorize resilience *per se*, which emerged decades earlier in the fields of applied ecology and process engineering and is not a novel understanding. Instead, the rapidly growing attention in applied policy settings to resilience concepts, bolstered by programmatic investments in adaptation and mitigation of global change, raises the need for closer scrutiny of *resilience-oriented policy*.

Resilience is the guiding principle and resilience policy is the aim in our recommendations and discussion of urban policy and planning for the water–energy nexus. Beyond considering uncertainty and the interlinkages between water and energy resources and the populations that rely on and govern them, *resilience-oriented policy* should integrate across sectors and be flexible to adapt to future uncertainty. This integration and flexibility can build the resilience outlined by Costanza (2012) by allowing systems to respond to greater magnitudes of stress in shorter periods of time. Policies could, for example, be explicitly made to encourage coordination, impact analysis, and long-term planning among agencies and the constituencies they serve. They could also support the creation of specific institutions at the city or regional level to spearhead development of adaptive capacity. This could link up with ongoing institutional sustainability building, like the green city effort described in Metro Vancouver (Sect. 3.2).

SES places a distinct emphasis on change, which may arise within or outside the coupled system and partially depends on the scale of the system. Endogenous change – change within the system – is seen as a product of internal dynamics, e.g., water abstractions for human purposes that degrade ecosystems and lead to irreversible biodiversity loss and impaired water availability or quality. Exogenous change – change occurring from external forces – results from broader regional or global dynamics, e.g., climate change, which may have profound local impacts but are not considered to be influenced by the coupled system. With increasing attention to landscape modification within cities, a subfield of urban SES has emerged (Tidball and Stedman 2013; Borgström et al. 2006). Yet the core concern of such studies remains coupled-system resilience within the cityscape. Inadequate attention has been paid to the impacts of urban growth on environmental quality at broader scales of global change, specifically for our purposes here, the implications of resource demands for water and energy of cities and urbanizing regions. These scalar sustainability challenges are discussed in our case study of Metro Vancouver, Canada (Sect. "3.2"). To better understand these challenges, we must consider the exercise of political power and economic resources commanded for the development and maintenance of cities as well as the physical infrastructure and operations required for long-distance provisioning of water and energy (Scott and Pasqualetti 2010).

The physical flows of resources, and institutions required for their provision, have been addressed by scholarship on societal metabolism and, for our purposes, the field of urban metabolism. Additionally, scholarship in urban metabolism that looks at the city as an ecosystem has raised important questions in relation to social equity, discussed more below. We agree with Williams et al. (2014) that it is necessary to consider the political implications of the nexus focus, particularly questioning the historical roots of water and energy management. While management schemes can appear to be apolitical, their implementation and institutional designs can privilege certain groups over others. Simply considering the resources together does not necessarily make the policies equitable or sustainable. The case study of Urban India below (Sect. 3.4) illustrates this point.

2.2 Urban Metabolism

While the ecological concept of metabolism explains specific cellular- and organism-level chemical processes to extract energy for life-sustaining processes and synthesis of new material, urban metabolism extends this metaphor to the city (Kennedy et al. 2011; Zhang 2013). Urban metabolism looks at the city as a giant organism or ecosystem and analyzes the inputs, transformations, outflows, and possibilities for recycling resources within the urban sphere (Zhang 2013). Examining the city as an ecosystem can inform sustainable urban design to encourage more efficient use and recycling of resources (Broto et al. 2012; Kennedy et al. 2011).

Urban metabolism examines the conversion of primary materials, water, and energy into human energy, waste, and urban infrastructure and land use (Broto et al. 2012; Decker et al. 2000). Kennedy et al. (2011) outline two fields of thought in urban metabolism: one looks at the energy conversion of cities in the terms of the ecologist Odum, and the second looks more broadly at the nutrients, resource intake, and outputs of cities as mass fluxes measured in joules. There are also critical theoretical approaches to urban metabolism, which examine the historical production of the urban environment and question the unequal distribution of resource access and environmental hazards (Gandy 2004; Heynen et al. 2006; Swyngedouw 2004). These approaches could frame the joint quantitative analysis of water–energy inputs and outputs, such as the approach described in the New Delhi case study below (Sect. 3.3).

There are different methodologies for assessing urban metabolism (see Broto et al. 2012 and Zhang 2013 for detailed discussions). Zhang (2013) provides an overview of the methodological avenues, with a focus on quantitative accounting and assessment methodologies and ecological footprint analyses. However, she points out that it remains to be resolved how to deal with environmental externalities. Furthermore, the ability to quantitatively measure the flows of resources into a city is dependent on available data (Kennedy et al. 2011). Kennedy et al. (2011) suggest that, despite limitations, urban metabolism is most useful for (1) sustainability indicators, (2) inputs to urban greenhouse gas accounting, (3) dynamic mathematical models for policy analysis, and (4) design tools.

The complementary and overlapping concept of social metabolism examines the energy or material that passes through the economy in a given area (Marull et al. 2010), and it turns analysis to economic–ecological measurement of energy and its impacts on land-use change (Fischer-Kowalski and Haberl 2007; Marull et al. 2010). Giampietro and Mayumi (2000) suggest that it provides a methodological means to explore sustainability in scientific terms, including the technical, economic, social, and ecological. In terms of the water–energy nexus, metabolism has been used for both understanding the production of energy (Haberl 1997; Giampietro and Mayumi 2000; Zhang 2013) and of water (Madrid et al. 2013) at multiple scales and in an integrated fashion. As highlighted by Madrid et al. (2013), in terms of water, this emphasizes the various states of water, the social construction of water scarcity, and the different scales of its production and consumption. It also highlights the importance of technology in mediating the efficient conversion of energy (Giampietro and Mayumi 2000).

In this chapter, we suggest that the concept of urban metabolism can provide a conceptual framework, and offers multiple methodological avenues, for sustainable urban policies centered on the water–energy nexus. As urban metabolism has been used for studying processes from all energy inputs to nitrogen flows (see Kennedy et al. 2011 for an extensive list of past studies), the water–energy nexus can provide a focal point in policy analysis for urban metabolism. Put differently, considering the city as an ecosystem highlights the multi-scalar connections among decision-making, resource access, and water and energy production, consumption, and management. The Tucson, Arizona, case study (Tucson, Arizona, and the Central Arizona Project: The Water–Energy Nexus as a Driver of Urban Expansion) discusses the multi-scalar dependencies between water and energy and why a holistic, ecological lens can be critical to identify and assess linkages between urban and regional scales. This lens provides a means to identify infrastructural and social vulnerability, while operationalizing sustainable development at the urban scale.

2.3 *Informing Policy*

Since global change inserts increasing uncertainty in resource flows and societal outcomes, resilience-oriented policy marks a departure from attempts to determine, a priori, the results of decision-making. Akin to adaptive governance but with a more articulated sense of multi-scalar linkages (local to regional to global), resilience-oriented policy utilizes multiple forms of integration, especially nexus approaches to resource use and its implications in social–ecological system terms. Uncertainty is less a question of what we do not know than it is an appreciation of the range of possibilities we must prepare for, not to overcome but to coevolve with. This notion of coevolving along with uncertainty requires a marked shift in urban planning and infrastructural design. Because these decisions are so context dependent, resilience can only be a guiding principle, not a list of set proscriptions.

In terms of sustainable urban planning and land-use policy, the urban water–energy nexus, understood through an urban metabolism framework, sheds light on how to improve urban planning and retrofitting practices to increase social equity. In terms of urbanization and climatic change drivers, the most globally pressing urban issues are resource access (primarily water, food, sanitation, and electricity) and exposure to pollutants and disaster risks. Urban flow patterns tend to benefit certain populations to the detriment of others; indeed, one major theme in urban metabolism literature is unequal access to resources and exposure to risk (Broto et al. 2012). Resilience polices must consider individuals, communities, and spaces which are most vulnerable to risk and uncertainty.

The many processes that constitute cities are reconfiguring water–energy relationships in broader spatial areas. This means urban policies must consider the networks within which they are embedded. Urban centers generally have greater access to financial, social, and political capital. These resources, along with institutional capacity, can be beneficial in implementing innovative strategies to reduce consumption, reuse waste, and recycle materials. Conserving water and improving efficiency can help reduce water and energy demands. While the coupled nature of water and energy can magnify the use of these resources, it can also lead to water and energy savings across sectors (Varbanov 2014). For example, Perrone et al. (2011) found that a 20 % decrease in water demand across all sources in Tucson, Arizona, corresponded to a 20 % decrease in water-related energy consumption. However, not all conservation methods necessitate energy savings. For example, water-efficient drip irrigation can be more energy intensive than flood irrigation (Cohen et al. 2004). The interlinked nature and associated trade-offs between water and energy consumption and production highlight the importance of a contextual nexus approach to evaluate opportunities and limitations with integrated systems.

The nexus framework can also inform policies which connect management of other related resources, such as waste. In support of the special interest of “waste as resource” to the United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), several of our case studies further explore the challenges and opportunities to reduce and recover waste in urban environments. The Delhi, India, case study (Sect. 3.3) specifically addresses water and energy nexus pollution implications and offers management recommendations for more sustainable policy and planning. Waste generation and recovery are discussed in Urban India (Sect. 3.4) regarding urban–rural gradients, and finally, the case study of Future Cities (Sect. 3.5) examines the potential of zero pollution in urban environments through urban design. To strengthen urban resilience in the face of global change uncertainty, nexus frameworks can foster resilient-focused governance. While there are many other factors that influence the nexus and could be included (e.g., environment, climate, and governance) in a “comprehensive” nexus, water and energy are the core resources, particularly in regard to wastewater, that are metabolized for urban development and human well-being.

3 Case Studies Relevant to the Urban Water–Energy Nexus

The urban water–energy nexus is location specific (Perrone et al. 2011). Differences in socioeconomic and political dynamics can create city-specific challenges and opportunities in water–energy management (Yang and Goodrich 2014). For example, regional differences influence the embodied energy, the GHG emissions, and energy costs of water (Mo et al. 2014). Detailed water–energy nexus analysis is therefore needed to develop city-specific management and adaptation options. Five case examples are summarized in Table 5.1 and discussed below to highlight both the key themes and diverse nature of the urban water–energy nexus.

Table 5.1 Summary of case studies relevant to the urban water–energy nexus

	Location	Case study	Theme, application
a.	Tucson, Arizona	The water–energy nexus as a driver of urban expansion	Urbanization Water and energy dependency
b.	Metro Vancouver, Canada	Sustainability assessment with urban metabolism and ecological footprint analyses	Urban metabolism Ecological footprint Sustainability planning and management
c.	Delhi, India	Applying the water–energy–pollution nexus to megacities	Evaluate water and energy nexus through consumption and production Assess sustainability for planning and management
d.	Urban India	Energy limits and competing institutional domains of wastewater	Resource consumption Waste generation and recovery Urban–rural gradients
e.	Future Cities	Urban design for resource efficiency and recovery	Urban retrofitting and design Resource efficiency Resource recovery Decentralized/hybrid systems

3.1 Tucson, Arizona, and the Central Arizona Project: The Water–Energy Nexus as a Driver of Urban Expansion

Southern Arizona has historically been the home to urban nuclei organized around the spatial and temporal distribution of accessible water supplies. Now, water and energy have reconfigured urban settlements in ways that generate new, unforeseen demand for these resources. The Santa Cruz River, with once-abundant riverine gallery forests situated in an extensive grasslands-dominated landscape, was capable of meeting human and ecosystem demands for water until the middle of the twentieth century. With the advent of steam- and subsequently electrical-powered pumps to extract local groundwater, aquifer drawdown began to present serious challenges for water supply and for urban infrastructure (roads and buildings) resulting from subsidence of the land surface as pumping dewatered the aquifer. The modern-day city of Tucson, located along the Santa Cruz, is in a climatic transition zone between winter-dominated rain/snow and Mediterranean-type climate along the western Pacific Coast (US state of California and northern Baja California peninsula in Mexico). The region has experienced rampant population growth, expanding from a few scattered indigenous and Spanish "urban" settlements in the early nineteenth century to several thousand in Spanish and Anglo communities at the turn of the nineteenth century to today's one million strong urban population in Tucson and adjoining satellite urban settlements of Green Valley, South Tucson, Tucson, Oro Valley, and Marana to the north and northwest along the Santa Cruz, Rillito ("little river"), Cañada del Oro, and other tributary rivers (now mostly dry). The rapid pace of change in urban expansion, river-water supply, and increasing reliance on groundwater would not be complete without an appreciation of public and private initiatives to command energy for water supply that in turn has driven urbanization in this chronically drought-prone region.

Tucson in the 1970s had expanded to a population of several hundred thousand (many with Midwestern US, temperate-zone predilections for lawns and swimming pools), which began rapidly outpacing local surface *and* groundwater supplies. Without going into the convoluted, but historically rich and resource resilience critical, questions of the Colorado River's trajectory, suffice it here to say that urban Tucson had outpaced its local water endowments. Half a century earlier, interstate negotiations on the Colorado River had resulted in a compact that allocated river water to seven US states (and subsequently in 1944, a portion to Mexico). What made the Arizona and California allocations particularly challenging, however, was the very major pumping that would be required to deliver Colorado River water to intended users and uses, largely in agriculture but with an undercurrent of urban supply in irrigated valleys that held water rights in prior-appropriation "first in time, first in right" seniority.

Of principal concern for our analysis, here, are the very considerable energy implications of pumping lift to supply water over long-distance inter-basin transfers. Enter the Central Arizona Project (CAP), which passed through several gestations to ultimately deliver Colorado River water to Phoenix and Tucson, Arizona's largest urban centers. Now, the nexus twist in the story is that dams on the Colorado River at Lake Mead and Lake Powell were originally developed to supply hydroelectric power throughout the region. Yet rapid urban growth and accompanying electricity demand soon outpaced the dams' generation capability, passing power demand to conventional, coal- and nuclear-based, thermoelectric generation. CAP as the largest single power demand in the state of Arizona (Hoover 2011) negotiated preferential arrangements with the Navajo Generating Station (NGS), located in Paige, Arizona, along the shores of Lake Powell. In order to supply Arizona's share of Colorado River water (1.5 million acre-feet) from below the downstream Lake Mead, over 1000 ft. of elevation and 360 miles of canal and pipeline, to Phoenix and further south but uphill to Tucson, CAP requires very significant amounts of power, which are met primarily by NGS, cooled using Colorado River water (Eden et al. 2011). Thus, a double nexus was created: Lake Powell water is evaporated to cool the coal-fired plant, which supplies electricity to pump water for Phoenix and Tucson.

Water demands for rapidly growing Phoenix and Tucson, together with wastewater reclamation and reuse, constitute an emblematic case of the urban water–energy nexus in Arizona, in which energy-intensive water supply (via CAP) is accompanied by pumped recovery of wastewater (from an extensive, low-relief sewer shed) and advanced treatment of effluent for multiple types of reuse. The key to Arizona's urban water and wastewater management is abundant and cheap electrical power.

3.2 Metro Vancouver: Sustainability Assessment with Urban Metabolism and Ecological Footprint Analyses

Urban metabolism studies indicate that consumption in urban areas is currently increasing in many developed cities (Moore et al. 2013). These results are particularly concerning given that many urban areas are currently operating under a biocapacity deficit, meaning their ecological footprint is greater than the region's biocapacity (WWF 2014). Although Metro Vancouver, Canada, is well known for its green design initiatives and sustainability commitments (Metro Vancouver 2010), Moore et al. (2013) calculated an ecological footprint for the region that was over 35 times the size of Metro Vancouver.

Metro Vancouver is a regional district in British Columbia, Canada, and includes the city of Vancouver as well as 22 municipalities. In 2006, the population of Metro Vancouver was approximately 2.1 million and covered an area of 283,183 ha. Water resources from the Coast Mountains are primarily gravity fed to Metro Vancouver and also used to supply hydropower. Hydropower accounts for 85 % of the region's electrical energy source with natural gas and some incineration of municipal waste making up the remaining 15 % (Moore et al. 2013). The city of Vancouver, which is part of Metro Vancouver, is striving to live within the global biophysical carrying capacity of the Earth and is working toward becoming the "greenest city" by 2020 (City of Vancouver 2014).

Combining an urban metabolism framework with a bottom-up ecological footprint analysis, Moore et al. (2013) quantified the materials and energy consumed by Metro Vancouver residents. These results were then compared to the global biophysical carrying capacity to assess sustainability. The authors applied a direct component approach, which combined urban metabolism, life cycle, and ecological footprint analyses. Available, reliable data from local authorities were used to estimate municipal energy and material flows by consumption category. Life cycle analysis was included in the energy and material consumption data to account for the embodied energy and material flow associated with manufacturing. Ecological footprint analysis was conducted in global hectares (gha). A global hectare assumes the productive capacity of 1 ha of land at world's average productivity (WWF 2014). This hybrid approach was used to create a robust and relevant analysis of Metro Vancouver's sustainability.

Metro Vancouver's ecological footprint for 2006 was calculated as 10,071,670 gha, which is over 35 times greater than the metro area. This area calculation includes the land needed to produce the goods and services consumed by Metro Vancouver and the land needed to assimilate the associated carbon dioxide emissions. The five major components of the footprint analysis were water, consumables and waste, buildings, transportation, and food (Fig. 5.1). Water, which had the largest material flow through Metro Vancouver, compromised only 0.34 % of the total footprint. Part of the reason for the low percentage was attributed to Vancouver's efficient gravity-fed water distribution system. Consumables and waste, buildings, and transportation had similar percentages, which were 14 %, 18 %, and 23 %,

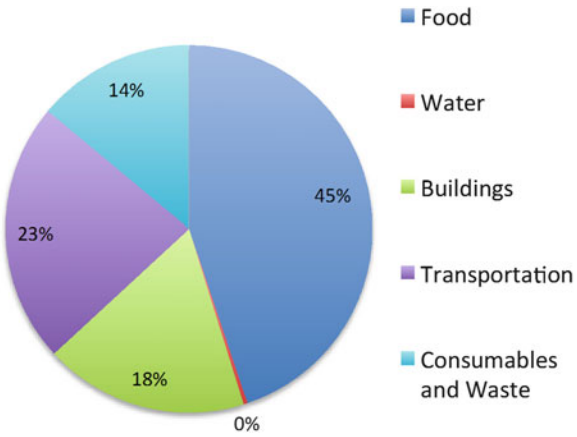

Fig. 5.1 Metro Vancouver's ecological footprint by component (Moore et al. 2013)

respectively. For consumables and waste, embodied energy and materials accounted for 92 % of the total carbon footprint. The remaining 8 % was a result of solid and liquid waste management. Within the buildings category, residential and commercial building use was significantly greater than the embodied energy of materials or the energy required for demolition and associated waste. Private transit accounted for 97 % of the transportation component with commercial and public transit making up the remaining three percent. Food, with 45 % of the total, accounted for nearly half of the footprint. The large footprint for food was attributed to the necessary land for agriculture and fodder as well as the energy-intense production, processing, and distribution of food throughout the city.

Despite local sustainability initiatives, Metro Vancouver residents are living beyond the global biophysical carrying capacity. Residents of Metro Vancouver have an average ecological footprint of 4.75 gha per capita. This footprint is almost twice the world's average biocapacity demand (approximately 2.7 gha/capita) and almost three times the world's biocapacity supply (approximately 1.8 gha/capita) (WWF 2010). These results indicate that if everyone on Earth had an ecological footprint the size of the average Metro Vancouver resident, it would take roughly three Earths to supply the necessary resources and assimilate the associated carbon dioxide emissions (Moore et al. 2013). The land needed to assimilate the associated carbon dioxide emissions ("energy land") is 58 % of the biocapacity demand, and 32 % of the needed land resources are for crops. The remaining three ecosystem types, forest, fishing, and pasture, make up the remaining 10 % of the needed land resources.

Rapid growth of urban areas combined with increasing consumption patterns will require more sustainable practices to live within the global biophysical carrying capacity. Quantifying ecological footprints for urban regions in terms of the geographical area and the ecological resource base can assist urban planners and resource managers to reduce ecological impacts and strive toward "one planet living" (Desai 2008).

3.3 *Delhi, India: Applying the Water–Energy–Pollution Nexus to Megacities*

The rise of megacities is expected to bring new global challenges to water, energy, and pollution. To reduce the negative water, energy, and pollution impacts of urbanization trends, Kumar and Saroj (2014) urge integrated approaches to more sustainably account and manage energy production and consumption, water use, and pollution. Kumar and Saroj (2014) evaluate the water–energy–pollution nexus of Delhi, India, to exemplify how a nexus approach can be utilized to systematically assess energy production and consumption. By incorporating pollution in the nexus, water and air quality are viewed as a salient component of the trade-off analysis for water and energy planning and management.

Water and air pollution are intertwined with energy production and consumption. Energy production and domestic and industrial applications of water resources generally result in deteriorated water quality. In turn, treating water resources and regenerating water quality require energy (Grant et al. 2012). Additionally, energy production from fossil fuels contributes to air pollution that is harmful to both the environment (i.e., greenhouse gases) and public health (i.e., particulate matter (PM), sulfur oxides (SO_x), nitrogen oxides (NO_x), and carbon monoxide (CO)). Understanding the relationships between water, energy, and pollution will be imperative to reduce energy consumption and harmful emissions especially as cities continue to grow and expand.

Delhi is one of the world's largest megacities. As of July 2013, Delhi, India (including Faridabad, Ghaziabad, and Gurgaon), had an estimated 25.3 million people. Currently the population is growing at approximately 3.3 % per year (City Population 2014). Megacities are hubs for economic growth, innovation, and development but also create large energy sinks. Energy demand in Delhi is greater than supply. From 2009 to 2010, the energy supply was 735 MW, a 3729 MW deficit from peak demand (4464 MW). To address shortages, long- and short-term power purchases are made from surrounding states, but supply still cannot always meet demand.

To evaluate the water–energy–pollution nexus of Delhi, Kumar and Saroj (2014) took a three-step nexus approach. They first examined the water–energy nexus by quantifying water and energy use. Delhi's energy supply was estimated to be about 14.2 GWh/day. This energy generation requires approximately 4.3 million m^3/day. About 25 % or 1.4 million m^3/day of this water is used for thermal processes. To supply, transport, and treat these water resources require approximately 2.2×10^6 kWh/day or about 15 % of Delhi's energy supply. Although water resource demand is relatively small compared to the total energy demand in Delhi, water resources play a significant role in the city's energy production and consumption (Kumar and Saroj 2014).

Next, Kumar and Saroj (2014) assessed Delhi's energy–pollution nexus. They focused on energy production and consumption from power plants and the transportation sector. Based on the supplied (735 MW) and peak demand (4464 MW), the estimated CO_2 emissions were 0.62 kg equivalent CO_2 emissions per unit energy (kWh) and 0.13 kg of human health emissions (including $PM_{2.5}$, SO_2, NO_x, CO, and VOC) per unit energy (kWh) produced. The total climate and health emissions for power plants and transportation were 0.65 and 0.49 kg of per unit energy consumed, respectively. Power plants had the greatest contribution to climate emissions, while the transportation sector had the greatest contribution to health emissions (Kumar and Saroj 2014).

Lastly, the water–energy–pollution nexus was evaluated. This more holistic approach highlights potential trade-offs and synergies to more sustainably manage water and energy resources. The results of the nexus analysis indicate that significant reductions in climate and health emissions are possible by using "greener" fuel and technology for power plants and transportation. Additionally, because energy demand for regenerating wastewater is relatively low, this resource could be capitalized for water supply, as well as benefiting public and environmental health.

Kumar and Saroj (2014) conclude that the water–energy–pollution nexus provides a holistic framework to systematically evaluate water and energy relations and assess sustainability in urban environments. Research to identify, understand, and quantify water–energy interactions is increasingly important for megacities such as Delhi, which are rapidly growing and expanding their energy sectors. Such knowledge about these urban relationships and trade-offs is needed to help inform policy and management decisions. Additionally, further work is needed to help facilitate the application of these urban water–energy–pollution nexus findings to reduce the negative impacts on water and air quality from energy development.

3.4 Urban India: Energy Limits and Competing Institutional Domains of Wastewater

Urban India (Fig. 5.2), close to 750 million inhabitants, equivalent to the urban population of the Western Hemisphere, ranges from megacities of Mumbai and Delhi to small towns. Each encompasses a particular nexus of water and energy, yet together they represent an urban network of resource consumption, waste generation and recovery, and overlapping institutional domains. Here, the urban–rural gradients of resource and institutional nexus dynamics are especially acute.

Chronically energy scarce (with electrical power rationing, high particulate matter emissions from biomass-based cooking and winter heating), cities in India have informal provisioning of water supply with minimal to nonexistent wastewater treatment. This is not to say that nutrients and water are not recovered (Amerasinghe et al. 2013). Instead, direct reuse of wastewater in urban and peri-urban agriculture is common practice.

Formalization of wastewater treatment implies consistent electrical power supply to maintain waste digestion and hydraulic circulation in treatment facilities. Absent captive power supplies, most urban waste recovery schemes utilize basic

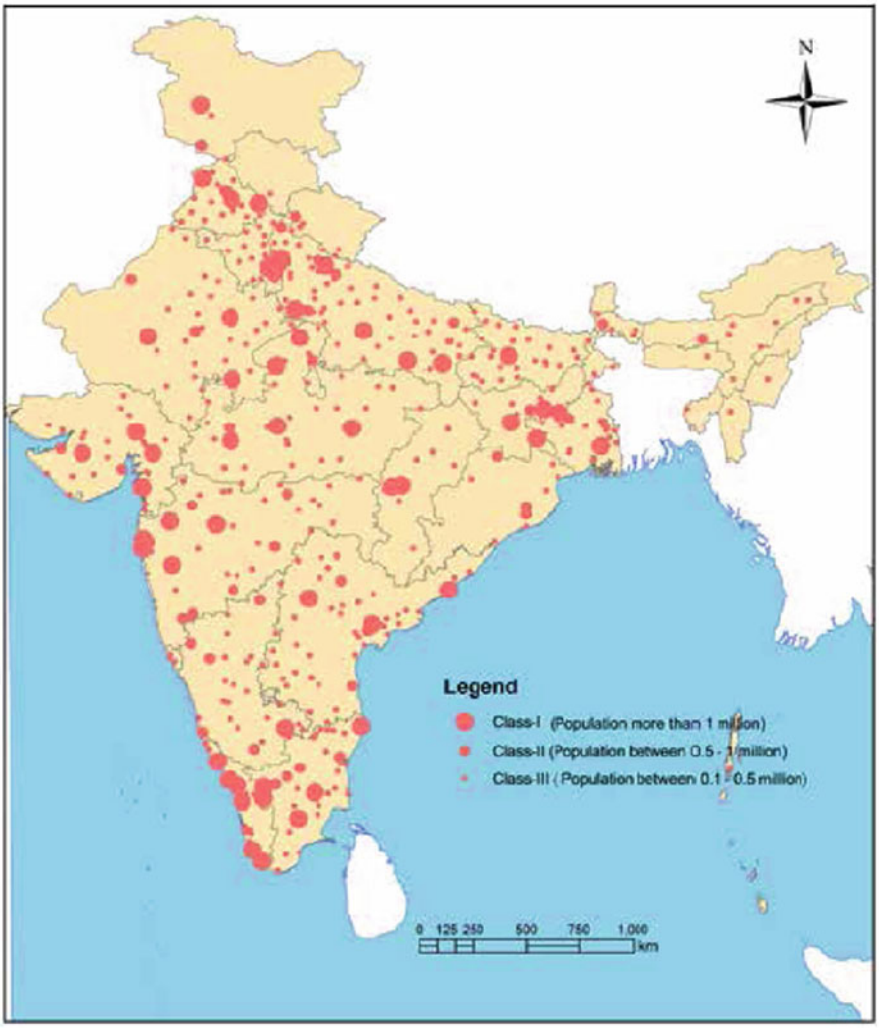

Fig. 5.2 Population distribution of Urban India, 2011 (Source: Census of India 2011)

primary sedimentation and oxidation, which are effective at a basic level of acceptability but require a large land footprint. As a result, most urban waste is simply released to receiving water bodies (and in turn become supplies for downstream uses of water). Ambitious efforts to enhance water quality in India's rivers will be stymied by erratic power supplies, implying a low optimal level of waste recovery. As has been demonstrated for Hyderabad, India, and other locations, however, this low level of capitalization and investment in infrastructure and operational inputs like electrical power has the unintended consequence of maintaining some degree of traditional access to resources. In other words, where resource recovery is based on investment, access to water and nutrients is often withheld from communities that have traditionally held usufruct rights to their use and benefits.

3.5 Future Cities: Urban Design for Resource Efficiency and Recovery

Urban development is rapidly expanding to meet urban population growth. The percentage of people living in urban areas is expected to rise from 54 % in 2014 to 68 % in 2050 (United Nations 2014b). The growth of "megacities" and "megaregions" create new challenges for sustainable water and energy development. Novotny (2013) presents a paradigm shift that highlights how "water-centric" urban green design and retrofitting can be used to achieve zero GHG pollution in future cities. This paradigm aims to connect landscape and technology to conserve water and energy resources and optimize resource recovery. In this model, water resources are recycled and reused at three scales (building, neighborhood, and city or regional level) within a hybrid or partially closed system. By synergistically eliminating waste and generating energy, this aspirational system can minimize environmental impacts from urban growth.

By focusing on water conservation and redesigning cities for water and energy resource efficiency and recovery, future cities can be planned, designed, and managed to improve resource sustainability and reduce GHG emissions. Novotny (2013) reviews the current status of resource recovery technologies for water resources and presents a vision for sustainable urban development. Novotny's paper is in response to the prevalence of unsustainable water use and management. While fields such as ecological economics have attempted to address the environmental externalities generated from this mode of decision-making, these externalities continue to be created. Furthermore, the "silo" and command-and-control frameworks fail to adequately address the complexity and multi-dimensions of water resources (Pollard and Du Toit 2008). As a result, conventional water resource management is failing to meet global challenges, and integrative management strategies are being promoted as an alternative (Rahaman and Varis 2005). Novotny (2013) embraces a holistic approach and envisions a fully integrated urban system that effectively reduces GHG emissions to zero. The cities of the future that he discusses are hypothetically designed or retrofitted to function as mostly closed systems. Water and energy resources are efficiently and effectively reused and recycled to minimize waste and promote sustainability.

Several methods are available to help assess integrated development and retrofit solutions. Water, energy, and ecological footprints help quantify resource use and productivity (Amarasinghe and Smakhtin 2014) as well as ecological impacts. These footprint analyses can be conducted for various scales and can also indicate the resource sustainability of urban metabolism. Furthermore, these tools can be used to contextualize and support resilience policies and the implementation of the

SDGs. What is particularly important is that the overall use of a resource is within sustainable limits.

When moving toward zero GHG emissions in urban areas, decentralized infrastructure needs to be implemented at all three scales: building, neighborhood, and city or regional (Novotny 2013). This includes conserving resources, reusing and recycling water, as well as resource recovery. At the house or building scale, water and energy conservation and recovery can be implemented through energy-saving devices such as xeriscaping, green roofs, passive heating and cooling, and the use of black water (water that includes organic solids and wastes) and gray water systems. Neighborhoods or "ecoblocks" can be seen as semiautonomous water management and drainage units. At this scale, water is cycled through the system with on-site reuse and centralized integrated resource recovery facilities (IRRF) for treatment. Regional IRRF's can help with recovery and production of water and energy resources. Black water, water that includes organic solids and wastes, can be salvaged for water, nutrients, solids, and energy. Anaerobic treatment processes produce methane, which can be captured and used. Solid waste can also be converted into syngas, which is a combination of carbon monoxide and hydrogen. Using fuel cell technology, carbon monoxide and methane can be converted to hydrogen. Carbon dioxide emissions can be captured and used for algal production, increasing biofuel. These water recycling systems are not completely closed; they will require clean water to mitigate the accumulation of contaminants such as salts, pharmaceuticals, etc., and will require safe disposal of non-reusable water. Although existing technologies are not economically viable for large systems, ongoing research and development is making them more competitive. In the future, these recovery facilities could treat water, produce electricity, and sequester carbon without contributing any pollution (Novotny 2013). IRRF can be designed "fit for purpose," which can have numerous benefits. These "fit for use or reuse" can also help transition between centralized and decentralized systems to link systems and increase efficiency (Nair et al. 2014). Linking "ecoblocks" together can lend itself to city- or regional-scale sustainability.

To evaluate the water and energy use and associated GHG emissions, Novotny (2013) evaluated three future alternatives. A summary of the alternatives, their assumptions, water demand, and results is provided in Table 5.2. The first alternative, Alternative I, assumes business as usual. It uses US household statistics assuming conventional water treatment and disposal and no water or energy conservation measures. The second alternative shows potential near future (10–15 years) water, energy, and GHG savings. Alternative II assumes that urban irrigation is cut in half through xeriscaping and water reuse. Using neighborhood scales, reclaimed water is treated by microfiltration and ozonization and is recirculated. Sludge is delivered and treated at an IRRF where methane is produced. Finally, the third alternative is based on a "Visionary 2050" future that fully embraces hybrid distributed systems to achieve zero pollution.

Increasingly, cities across the globe are recognizing the need to adapt to new knowledge, understanding, and management of water resources. Cooperative initiatives are bringing together diverse stakeholders including urban planners, landscape

Table 5.2 Alternative systems for future cities presented by Novotny (2013)

	Assumptions	Water demand (liters/capita/day)	Results
Alternative I: business as usual	No water or energy conservation	550	1.26 tons of CO_2 emissions per capita per year
	Conventional water treatment and disposal		
Alternative II: near future (10–15 years)	Reduce irrigation by half (xeriscaping and reuse)	166	CO_2 equivalent emissions reduced by up to 75 %
	Some reuse and recycling of water through IRRF		
Alternative III: "Visionary 2050"	Citywide "water-centric" hybrid distributed system that includes double-loop reuse	50	Energy surplus equivalent to 1 MW for community of 10,000
	Co-digestion of food and waste		

architects, environmental engineers and scientists, and decision-makers. Cities, such as Birmingham, United Kingdom; Hamburg, Germany; Lodz, Poland; Zaragoza, Spain; Beijing, China; and Seattle, Washington, have developed citywide alliances to improve sustainability through interdisciplinary learning and development (Novotny 2013). These liaisons are helping cities overcome challenges from conventional water and energy management by breaking down horizontal and vertical barriers and promoting innovative and integrated frameworks. As urban areas continue to grow in population and their demand for natural resources increases, resource conservation, efficiency, and recovery can provide feasible alternatives to conventional resource use and management that reduce GHG emissions and promote resource sustainability.

4 Planning for Urban Water–Energy Nexus Processes

The case studies above provide different scalar and conceptual approaches to analyzing, designing, and modeling the urban water–energy nexus. The parameters for the nexus are constantly changing. Urban form and density, dependence on infrastructure within and beyond the city, the concentration of political and economic power, and rapid growth punctuated by boom and bust cycles (illustrative of thresholds in SES terms) all drive the interplay of water and energy in distinct ways. Considering these multi-scalar challenges, we outline dimensions to plan for resilient systems with urban water–energy linkages.

4.1 Regional Planning for the Urban Nexus

Although the city is the unit of analysis, water and energy, among other resources and flows, are intrinsically linked across rural–urban gradients. Patterns of connection – physical, environmental, social, and institutional – between the city and rural regions are sometimes taken to be the nexus linkages of principal concern. Resources and institutions form the nexus, which can be manifested in urban and rural spheres and across the rural–urban gradient. Rural and urban populations face concerns over environmental degradation as well as the availability, affordability, and accessibility of water and energy resources. While these challenges are widespread, water–energy interactions can significantly vary between rural and urban populations.

In terms of policy and planning for urban resilience, it is important to look at the broader effects of the urban consumption of resources on surrounding rural populations and land-use patterns (Madrid et al. 2013; Zhang 2013). Urban metabolism literature in particular has homed in on the effects of economic drivers on urban–rural relationships, that is, the flows of resources, materials, and waste between urban and rural areas (Broto et al. 2012). It is not only necessary to consider land-use impacts but also the efficiency of energy and material conversion when analyzing urban–rural flows (Marull et al. 2010), such as the concerns raised in the Tucson case study (Sect. 3.1).

While there is often no clear line between the urban and the rural (see Sect. 3.4), population density influences the distribution and consumption of resources. Urban areas can often, however, more efficiently distribute resources than rural regions. Energy efficiency is optimized for population densities between 80 and 200 people per hectare (Novotny and Novotny 2012; Novotny et al. 2010). Although there is greater potential for efficient resource delivery and use, urban areas also allow for increased consumption and associated waste production. Evaluating ecological footprints in modern cities, Wackernagel et al. (2006) found that even though residents had smaller per-capita transportation and housing impacts, their increased affluence significantly amplified consumption and their overall ecological footprint – an example of the social-equity dimensions of the resource nexus. In addition to high consumption, cities also produce 75 % of all GHG emissions (UNEP 2014). Comparing water–energy interactions, trade-offs, and impacts for various population densities can help further our understanding of how the water–energy nexus varies across scales. While the city as organism metaphor is incredibly helpful for planning, uneven historical urban development can continue to make certain populations more vulnerable to hazards, uncertainty, and inability to access resources.

Although integrated approaches are needed to more equitably and sustainably manage water and energy resources, the water–energy nexus is highly variable. Regional and local assessments are needed to capture the heterogeneity of water–energy relations (Siddiqi and Anadon 2011). Water infrastructures, particularly the embodied energy, energy costs, and GHG emissions associated with distribution, vary regionally (Mo et al. 2014). In rural regions, distributing water and energy can be quite expensive per capita and difficult to implement. The weight and bulk of water, along with the sheer quantity often needed for human consumption and agricultural or energy production, among other uses, make it energy intensive and thus expensive to transport, store, and distribute. However, in urban environments, the aging and decay of water infrastructure can lead to loss of water and higher energy costs for distribution. Evaluating these local or regional differences is necessary to adequately assess water–energy relationships and develop appropriate site-specific policies that reduce water and energy consumption and associated GHG emissions.

When examining urban–rural relationships, it is also important to consider the spatial distribution of the water–energy nexus. The proximity of humans to a given water source and to sanitation treatment facilities, along with the degree and type of water and sanitation treatment, influences energy use and associated costs. For example, snowmelt, gravity-fed water distribution systems (e.g., Vancouver, Canada) will have lower energy requirements due to reduced distribution and treatment than cities that rely on large-scale water transportation schemes (e.g., Phoenix, United States) or energy-intensive treatment such as desalination (United Arab Emirates, United States, Israel, or Saudi Arabia).

Similar to water, the availability and accessibility of food and materials greatly impact the embodied energy and virtual water required to obtain, transport, and distribute these resources. Embodied energy and virtual water vary between urban and rural communities. Cities are often spatially disconnected from the resources used to support them in their metabolic processes. Food is one such example. Because over 70 % of water withdrawals globally are for agriculture (Rost et al. 2008), food is typically an additional component of the water–energy nexus, often more physically connected in rural regions. Transporting food and materials is energy intensive and typically relies on petroleum-based fuels, which are a large contributor to GHG emissions. Life cycle analysis of urban goods indicates high embodied-energy costs as well as large quantities of virtual water (Droege 2011 and Moore et al. 2013).

Cities can leverage their urban resources such as financial, social, and political capital as well as institutional capacity to make large strides in resource conservation, efficiency, and recovery. Because consumption per capita is generally greater in cities (UNEP 2011; Wackernagel et al. 2006), there is great potential to reduce consumption and waste generation. Furthermore, high population densities lend themselves to cost-effective reuse and recycling of materials. The possibility for the recycling of resources can often become more cost effective in more developed cities (Zhang 2013). Additionally, green design and peri-urban agriculture are some initiatives that are being pursued to increase urban sustainability. These topics are discussed in further detail in the next section.

Differences in population density and geographic location necessitate region-specific water–energy nexus assessments. These assessments can help identify synergies and trade-offs to improve the sustainability of water and energy use and management. Understanding the coupling of water–energy at different locations and scales will be imperative to assist with planning and decision-making to improve resilience policies and water and energy security.

4.2 Infrastructure: Nexus Role, Impact, and Policy Lever

Although technology can provide innovative solutions to improve efficiency, these solutions can also increase vulnerability. Williams et al. (2014) warn of assuming integrative management will lead to sustainable solutions. Desalination, water transfers, and biofuel energy all aim to increase water or energy supply and, in turn, also increase reliance between water and energy sources thus potentially increasing vulnerability. In contrast, decentralized systems, which can reduce the reliance of energy on water systems, can help reduce vulnerability. While specific examples are provided below, our intent is to demonstrate that linked infrastructure systems, e.g., water supply networks tied to electricity grids relying on interconnected water sources for power generation, can be susceptible to cascading failure and slow recovery (Grubesic and Murray 2006). Thus, modularity and redundancy must be highlighted as resilience principles.

Decentralized water systems are being promoted to build resilience to future uncertainty (Nair et al. 2014). Decentralized systems are defined by Cook et al. (2009) as “systems provided for water, wastewater and stormwater services at the allotment, cluster and development scale that utilize alternative water resources, including rainwater, wastewater and stormwater, based on a ‘fit for purpose’ concept”. “Fit for purpose” systems are designed to supply a specific quantity and quality of water for a given purpose. For example, if gray water is used for irrigation, then the water is treated to meet irrigation requirements and would retain nutrients to reduce the use of industrial fertilizers. With these “fit for purpose” designs, wastewater or stormwater treatment systems can be designed to meet household, local, or regional needs. These decentralized systems, also known as on-site systems, can be managed independently or be integrated into centralized systems. They can help diversify management options with alternative infrastructure that embrace multiple sourcing with green and regenerative design principles such as rainwater harvesting, passive water treatment, aquifer recharge, and water reuse.

Green and regenerative designs and infrastructure, as discussed in the Future Cities case study, offer opportunities to conserve water and energy resources through efficiency improvements and passive treatment. For example, drip irrigation or rainwater gardens reduce water consumption, and green design such as pervious pavements and infiltration ponds can help with aquifer recharge and stormwater management. Some development projects that implement green and regenerative design include the Centre for Interactive Research on Sustainability at the University of British Columbia (Cole et al. 2013), Solaire Battery Park residential complex in New York City, and Olympic complexes in Beijing and London (Novotny 2013).

4.3 *“Waste” and Resource Recovery*

Reusing water through resource recovery has shown to be a viable option to increase water supply, particularly in regions where conventional water supplies are energy intensive (see Sect. 3). Using a holistic energy–water analysis that included water treatment, distribution, and discharge of water supply scenarios for the US coastal cities of Tampa Bay, Florida, and San Diego, California, Mo et al. (2014) found that reclaiming water resources had lower embodied energy, GHG emissions, and associated energy costs compared to expanding traditional water supplies or developing seawater desalination. Additionally, Siddiqi and Anadon (2011) found that if Libya, Qatar, and Kuwait recycled a quarter of their annual wastewater, they could likely meet their industrial water demand. Recycling water would be less energy intensive than expanding the energy-intensive conventional supplies, which are predominately groundwater pumping and desalination. A few cities that are currently implementing resource recovery include the “ecocities” of Qingdao, China; Masdar, United Arab Emirates; and Hammarby Sjőstad, Sweden (Novotny 2013).

Despite the energy, economic, and GHG savings from reclaiming water resources, there are social and political obstacles to implementation. There is public resistance to recycled water as well as potential health concerns (Mo et al. 2014). Furthermore, the institutional capacity to handle and support integrated policy is limited (Hussey and Pittock 2012).

4.4 *Climate Adaptation and Resilience*

There is rapidly expanding concern for climate change impacts on urban centers, heightened particularly by catastrophes wreaked by Hurricane Katrina in New Orleans and Sandy in New York and New Jersey, São Paulo’s hairsbreadth precarious water supply contingency in the face of drought, or Sydney’s recurring threat of devastating wildfires. Populations, real estate, and infrastructure are all especially vulnerable. Yet cities and urban residents often demonstrate incredible resilience in the face of global environmental change – often a result of adaptive capacity, institutions and organizations created for response, external investments in post-disaster recovery, etc. In other instances, vulnerabilities persist, seeming to await the next round of crisis and partial, inadequate recovery.

The heavy reliance on urban infrastructure can cause a “resource trap,” that is, disaster-ravaged cities are compelled to rebuild along the same lines of water, energy, transportation, and communications systems that may have exacerbated the human and ecological effects of extreme events. In this sense, deliberative planning, accounting for water–energy interlinkages and their impacts on service provision and other infrastructures, and long-range intentional, or guided, coevolution toward more resilient cityscapes and urban settlements can be examples of virtuous nexus cycles.

5 Moving Forward: Sustainable Development Goals Relevant to the Urban Water–Energy Nexus

In June 2012, the United Nations Conference on Sustainable Development (Rio + 20) was held in Rio de Janeiro. A 30-member working group was identified to establish "aspirational and easy to communicate" Sustainable Development Goals (SDGs). These SDGs are scheduled to replace the United Nations Millennium Development Goals (MDGs) after 2015 (United Nations 2014a).

The SDGs are designed to promote a more universal and holistic approach to development than the MDGs. Weitz et al. (2014) explains, "while the MDGs aimed to *lift* people out of poverty, the SDGs aim to *keep* them out of poverty." Although the SDGs have not been finalized, there are currently 17 goals and 169 targets, which aim to end poverty and hunger, improve human health and education as well as global justice and equality, and promote human and environmental sustainability by reducing greenhouse gas emissions, protecting ecosystem services, and supporting resilient communities.

While some targets are open ended with no set date, the majority of the targets aim to be achieved by 2020 or 2030. Several goals are directly tied to the urban water–energy nexus. Goals 6 and 7 specifically address water and energy security, respectively, and goal 11 focuses on urban development. These goals are listed below (United Nations 2014a):

- Goal 6: Ensure availability and sustainable management of water and sanitation for all.
- Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all.
- Goal 11: Make cities and human settlements inclusive, safe, resilient, and sustainable.

Some additional goals that are relevant to the urban water–energy nexus include:

- Goal 2: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture.
- Goal 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment, and decent work for all.
- Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.
- Goal 12: Ensure sustainable consumption and production patterns.
- Goal 13 Take urgent action to combat climate change and its impacts.
- Goal 17: Strengthen the means of implementation and revitalize the global partnership for sustainable development.

Acknowledging that the United Nations Framework Convention on Climate Change is the primary international, intergovernmental forum for negotiating the global response to climate change (United Nations 2014a).

Many of the SDGs are crosscutting and intended to support multiple objectives. These goals recognize relationships across sectors and promote an integrated and holistic approach for sustainable development. For example, accessible water resources and affordable energy are necessary to ensure food security. Furthermore, the goals aim to be universally applicable and to help all countries promote sustainable development. By further exploring the region-specific synergies and trade-offs between water and energy, the water–energy nexus can be a powerful tool to guide policy to support the SDG goals and targets.

Because the SDGs are broad and aspirational, there is ongoing discussion and research about how to implement these goals and meet targets. A multitude of papers urge using integrated nexus frameworks to develop sustainable pathways for effective development. Weitz et al. (2014) examine the importance of the water–energy–food nexus to address SDGs; Nilsson et al. (2013) explore integrated eight layers of the energy sector for SDGs; Rivera (2013) focuses on bridging policy and science in urban environments to address city-specific needs; and guidance on governing water to meet SDGs is presented by Sindico (2014).

Following this nexus scholarship and leadership in designing the SDGs to be crosscutting, especially in regard to the urban realm, we reemphasize the importance of looking at the city as an organism and designing policies which consider the multifaceted connections among resilience, water and energy production, consumption, and management.

6 Conclusions

The urban nexus comprises both water–energy resource linkages and institutional dynamics. Our definition and assessment of the urban water–energy nexus aims to offer an urban-focused conceptual approach with important lessons for the SDGs and beyond. This is designed for institutions related to urban governance, as well as state- and national-level resource and infrastructural planning. Put differently, the urban water–energy nexus implicates institutions that intersect multiple governance levels and urban–rural gradients. By using the urban water–energy nexus as a policy framework, more integrated, sustainable, and resilient planning for urbanization and urban processes are highlighted.

The case material presented above highlights several research gaps in the nexus approach, e.g., water and energy consumption and production in industrial and commercial operations or peak loads in water and energy demand as opportunities to harness the urban water–energy nexus (Kenway et al. 2011). While our chapter does not attend to the legal frameworks of water and energy as they relate to governance and decision-making, we recognize the importance of studies of this nature (e.g., Bauer 2009) and believe this is a dimension of the nexus that merits more scholarship and applied work.

Examining water–energy nexus interactions across rural–urban gradients, we see how urbanization is changing agricultural practices and reshaping global water (and energy) demands (Siddiqi and Anadon 2011). Additional work is needed to more explicitly show the changing nature of the nexus from urban-based, infrastructure-dependent resource use practices like desalination for urban water supply to more rural-situated nexus dynamics like the irrigation–electricity nexus that is a key to understanding global food systems. This research can help inform water and energy sectors to create more integrated and flexible policy and planning to enhance resilience to global change.

The nexus captures the coevolution of environment and society at the broadest level but places special attention on multiple scales of resource use. Innovations in nexus approaches to urban metabolism include the incorporation of the concept of "waste as resource." Short-term conservation, reuse, and efficiency improvements are needed alongside long-term policies and regulation that support integrated management and resilient systems (Varbanov 2014). However, institutional mandates may be confounded (pollution abatement vs. local-use practices, economic objectives vs. environmental quality associated with "waste," etc.), potentially placing adaptation and resilience policy at odds with local social and environmental agendas. Thus, additional research in urban water–energy nexus studies and practice must assess waste and resource recovery, including the opportunities and limits to efficiency gains.

Acknowledgments The authors gratefully acknowledge the support of the United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES). This research was also partially supported by the CGIAR Research Program on Water, Land and Ecosystems; the Inter-American Institute for Global Change Research, via project CRN3056, which is supported by the US National Science Foundation (NSF) grant no. GEO-1128040; and NSF grant no. DEB-1010495.

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Part III
Population Growth and Increased Demand for Resources

Chapter 6
Role of Soils for Satisfying Global Demands for Food, Water, and Bioenergy

Winfried E.H. Blum

Abstract The large increase in food production in the second half of the last century, mainly through the “green revolution” and further positive developments, especially the use of fertilizers and plant protection products, could not prevent the situation that today nearly one billion people live with hunger, mostly because of lack of access to food. In total, about four billion people can be considered malnourished, due to further specific nutritive deficiencies. The sustainable production and availability of food is also increasingly threatened by impacts deriving from human activities, especially changing forms of land use at local and global scales. Most critical are soil losses through sealing by urbanization, industrialization, and transport, probably the most important threat to food security at all, but also erosion by water and wind and further severe forms of soil degradation, such as loss of organic matter, contamination, loss of soil biodiversity, compaction, salinization, nutrient mining, desertification, and flooding, endanger food security. Climate change as well is threatening food security directly with increasing losses and degradation of soil, mainly through extreme events. In many regions, a decrease of freshwater resources is threatening rain-fed and irrigation agriculture. Meanwhile, there is a serious competition for space, energy, and water emerging from biofuel production and a concomitant increase in demand for food and fiber on local and world food markets.

1 Introduction: Soils and the Sustainable Development Goals (SDGs)

A look into the overall dimensions of the seventeen sustainable development goals, proposed by the Open Working Group of the General Assembly of the United Nations, raises the question about the role of nature in the realization of all these goals. Doesn’t nature have its own right of existence independently from human

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H. Hettiarachchi, R. Ardakanian (eds.), *Environmental Resource Management and the Nexus Approach*, DOI 10.1007/978-3-319-28593-1_6

interests? Isn't human life part of nature and therefore intimately linked to its functioning?

On one side, the SDGs focus on improving the existence, well-being, and the general interests of humans, and on the other side, they also target the protection of the environment and its natural resources, such as climate (SDG 13), oceans (SDG 14), and terrestrial ecosystems (SDG 15).

Without respecting and protecting these resources, the many SDGs aiming at securing and improving human life cannot be realized, because humans are part of nature and have to respect its basic rules.

In the following, we will not only discuss the role of soil functions for achieving SDGs but also harness the threats against soils, which compromise the sustainable use of land and soil resources. A number of SDGs cannot be achieved without them; see also Bouma (2014).

From the 17 SDGs, goal no. 2, "End hunger, achieve food security and improved nutrition and promote sustainable agriculture," is mainly linked to soils and their functioning in natural environments. There are two other goals, no. 6, "Ensure availability and sustainable management of water and sanitation for all," and no. 7, "Ensure access to an affordable, reliable, sustainable and modern energy for all," which are only to some extent related to soil and land. For this reason, we will discuss goal no. 6 under the aspects of availability and sustainable management of water and goal no. 7 with regard to the provision of energy, with a special focus on bioenergy under goal no. 2, targeting food security and sustainable agriculture.

In the following, we will discuss the functions of soils and how land and soil can satisfy global food demands, as well as demands for water and energy. As healthy food and clean water are the two basic needs for human life, we will focus mainly on these two aspects.

1.1 Land, Soil, and Soil Functions

Land means the land surface and includes the soil as its most important component.

Soils are three-dimensional bodies at the land surface with liquid, gaseous, and solid components containing inorganic and organic materials, including living organisms in a great number and variety; see Fig. 6.1. Because of their extremely slow development, soils are a nonrenewable resource.

Soils have six main functions, which are of importance for humans as well as for the natural environment (Blum 2005); see also Commission of the European Communities (2006):

- Production of plant biomass, ensuring food, fodder, and renewable energy by disposing physical, chemical, and biological conditions for plant growth. This function is the basis of all human and animal life, and therefore, it is the main function for targeting SDG no. 2 but also the basis for the generation of bioenergy; see SDG no. 7.

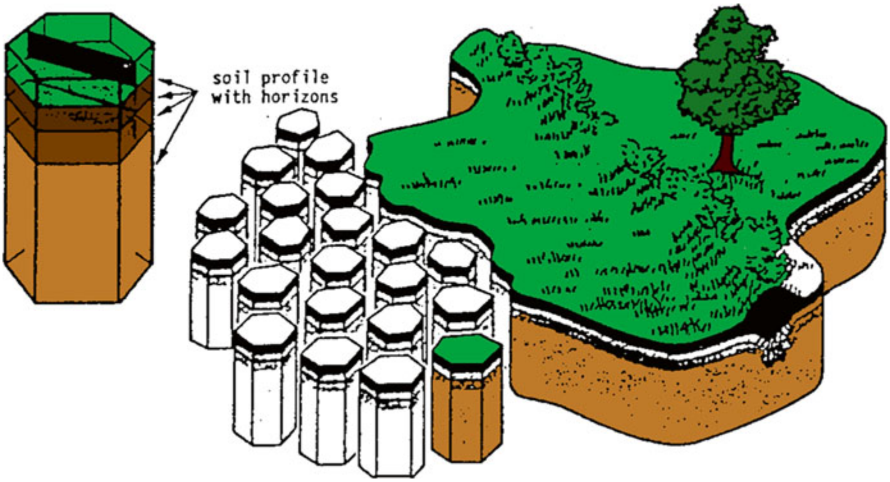

Fig. 6.1 Land surface (*right*) with soils as most important land components (*left*)

- Filtering and buffering through adsorption and desorption of inorganic and organic components at the soil inner surfaces, thus disposing nutrients for plant growth. Through filtering and retaining contaminants deriving from environmental pollution or detoxification of organics through biological transformation, they protect the food chain and the groundwater against contamination. With regard to SDG no. 6, these functions allow the filtering of rainwater and the generation of clean groundwater resources for human consumption.
- Maintaining and protecting soil biodiversity means protecting the largest gene reserve of the globe, 3–4 times larger in biomass and number of species than all biota at the soil surface together.

In addition to these three ecological functions, land and soils have three further technical, economic, and social functions:

- Soils are the basis for the development of technical infrastructures for human living and the production and exchange of goods and services, such as houses, industrial premises, roads, and dumping of refuse as well as sports and recreation facilities. For these purposes, soils are sealed, losing mostly all of their ecological functions.
- For the implementation of these infrastructures, land and soils serve as a source of mineralic raw materials, such as clay, sand, gravel, or stones, and as a source of water, mainly groundwater. In regions where no stones or gravel is available, fertile soils are excavated and used for the production of bricks and tiles because of their clay and silt content, in many areas compromising food security.
- Finally, soils are a natural and cultural heritage, forming and concealing cultural landscapes and protecting paleontological and archeological treasures as a kind of historical memory, which allows us to understand the history of humans and of their natural environment.

With regard to the satisfaction of the SDGs, the three ecological soil functions are of main importance.

1.2 Land Management and SDGs

SDGs can only be reached by sustainable land management, specifically agricultural land management – therefore, the question arises: what is sustainable agricultural land management?

Figure 6.2 depicts the goods and services, which can be delivered by sustainable agricultural management. This figure shows clearly that agriculture should not only produce biomass in the form of food, fiber, and bioenergy in the top of the soil but also sufficient and clean groundwater underneath, because each drop of rain falling on the land has to pass the soil before it becomes groundwater, which disposes in many cases the only drinking water resource. The agricultural management and plant production on the topsoil (especially the use of agrochemicals) therefore need to be harmonized with the groundwater production underneath in quantity and quality.

Moreover, soil management should minimize or avoid surface runoff of soil material into open water resources, such as lakes, ponds, and rivers, because it may be likely that these waters are loaded with chemical compounds and sediments, leading to eutrophication and blocking of waterways, respectively.

As soils are in direct gas exchange with the atmosphere and emit climate-relevant trace gases such as carbon dioxide CO_2, methane (CH_4), and dinitrous oxide (N_2O), agricultural management should control and minimize the production of these gases, thus mitigating climate change (see SDG no. 13).

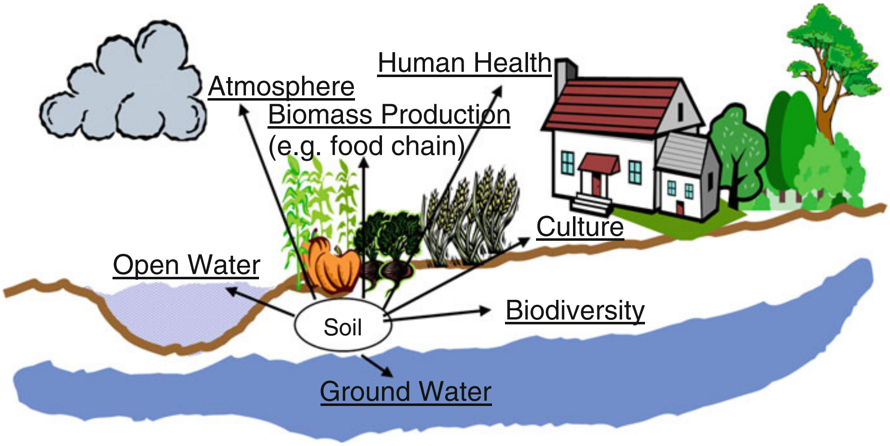

Fig. 6.2 Goods and services provided by land and soil (Blum 2007)

Soil biodiversity is of paramount importance for all mentioned soil processes related to food production and to the protection of groundwater resources. Soil biodiversity as well is directly linked to the aboveground biodiversity, including pests and diseases which endanger food production and storage. Even human health is likely to be influenced, directly or indirectly by chemical and biological soil components, depending on soil management (Brevik and Burgess 2013); see also SDGs no. 3 and no. 15.

However, the delivery of goods and services by sustainable agricultural land management, especially the sustainable production of food (SDG no. 2), depends to a large extent on the quality and special distribution of the global soil resources; see Sect. 2.

1.3 SDG No. 2 and the Complex Issue of Food Security

SDG no. 2 is aiming at food security and is therefore predominantly linked to soil and soil functions.

The 1996 World Summit agreed that food security represents “a situation that exists when all people, at all times, have physical, social, and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life” (Barrett 2010).

This definition comprises complex targets, because food security means not only to have food available through sustainable production but also to have access to food under different conditions. Table 6.1 explains the complex issue of food security, distinguishing between availability/sustainability and accessibility.

Availability (production) encompasses environmental, social, and economic as well as technological opportunities and threats, for example, the availability of natural resources such as land surface, topography, soils, water, biota, climatic conditions, and others. Moreover, human and capital resources, as well as farming systems, land ownership, and food policy systems, in addition to the availability of tools, for example, agricultural machinery, as well as agrochemicals (plant protection products, fertilizers, etc.), are important.

Food availability is very different from food accessibility by individuals or groups of individuals, because there are a number of constraints, such as physical accessibility (e.g., through storage, transport, market conditions, quality and safety control, and others) and economic and social accessibility, which are mainly determined by food policies at national and international levels, pricing systems, and income generation, because most people need to purchase food.

Cultural accessibility is most significant and very diverse at a worldwide level due to different food habits based on worldviews, myths, religions, and cultural perspectives in general. Finally, because of different genetic constitutions, the physiological accessibility to certain types of food differs worldwide, depending also on the health conditions of individuals. The worldwide increase of allergies is an example.

Table 6.1 The complex issue of food security

Focus area	Topics	Subjects
Availability/sustainability (=sustainable food production)	1. Environmental opportunities/threats	Natural resources: land surface, topography, soils, water, biota (animals, plants), climatic conditions, etc.
	2. Social/economic opportunities/threats	Human resources, capital resources, farming systems, land ownership, food policy systems, etc.
	3. Technological opportunities/threats	Available tools (e.g., machinery), agrochemicals, etc.
Accessibility	1. Physical accessibility	Storage, transport, market conditions, quality/safety control, etc.
	2. Economic/social accessibility	Food policy, pricing systems, income generation, etc.
	3. Cultural accessibility	Food habits, worldviews, myths, religions, etc.
	4. Physiological accessibility	Genetic constitutions, health conditions, for example, allergies, etc.

Concerning the discussion of food security in relation to soils, the focus is mainly on the availability aspect, which means the aspect of sustainable food production by sustainable agricultural management. This depends on the availability of natural resources, summarized under “environmental opportunities and threats,” such as available land surface, topography, soil distribution and soil quality, and water availability, availability of natural biota and husbandry animals and plants (e.g., seed material), and climatic conditions. The complexity of this approach is shown in detail by Mueller et al. (2010).

2 Global Land and Soil Resources: Their Quality and Spatial Distribution Including Population

In the following, we will discuss the quality and spatial distribution of the global land and soil resources including the population.

Table 6.2 Global soil distribution (by orders/soil taxonomy) and population

	Land		2014 population	
Soil orders[a]	Area 10^6 km^2	%	Population 10^6	%
1. Total ice-free land/population	128.57	100	7200	100
2. Kind of soils (a detailed description of soils by orders is given in Table 6.3)				
Alfisols	11.52	8.96	1217	16.9
Andisols	0.84	0.65	122	1.7
Aridisols	14.34	11.15	396	5.5
Entisols	19.30	15.01	1145	15.9
Gelisols	10.29	8.00	29	0.4
Histosols	1.40	1.09	36	0.5
Inceptisols	11.73	9.13	1412	19.6
Mollisols	8.23	6.40	475	6.6
Oxisols	8.96	6.97	281	3.9
Spodosols	3.06	2.38	122	1.7
Ultisols	10.08	7.84	1274	17.7
Vertisols	2.89	2.25	396	5.5
Shifting sands	4.86	3.78	94	1.3
Rocky land	11.93	9.28	194	2.7
Glaciers, water bodies	9.14	7.11	7	0.1

[a] Soil Survey Staff (1999)

2.1 Land, Soil, and Population

A view on the worldwide distribution of the very different land and soil resources and their quality for food production may help to understand the actual global problems of food security; see also Blum and Nortcliff (2013).

Blum and Eswaran (2004) illustrated the global distribution of soil and land resources based on the 11 soil orders of soil taxonomy (Soil Survey Staff 1999) and corresponding populations. The population data have been adjusted to reflect the 2014 estimate of global population (7.2 billion). Table 6.2 presents the land area occupied by each soil order and an estimate of the number of people living on each one. A key to the 11 soil orders is presented in Table 6.3.

Ultisols, Alfisols, Inceptisols, and Entisols (see Table 6.3) have high populations, together supporting over 70 % of the world population. This group of soils presents favorable conditions for agriculture but represents only 41 % of the land area.

Historically, on these soils, communities first settled on alluvial plains and low-relief undulating land that required low traction for management. At a later stage, also soils with former constraints to agricultural management, such as Vertisols and Aridisols, could be used more intensively through technological developments.

In temperate parts of the world, Alfisols and Mollisols show high concentrations of people. The Mollisols occupy about 6.4 % of the land surface and hold about

Table 6.3 Key to the soil orders of the "soil taxonomy" (Soil Survey Staff 1999)

Alfisols	Well-developed soils with clay accumulation horizons, weakly acid–acid, with medium to high base saturation
Andisols	Soils developed on volcanic rocks and aeolian deposits, with specific mineralogical characteristics, acid, with brown to dark brown colors
Aridisols	Weakly developed soils in arid and semiarid environments
Entisols	Young soils without distinct diagnostic horizons
Gelisols	Soils with permafrost
Histosols	Soils with high accumulation of organic matter, including fen and moor
Inceptisols	Weakly weathered soils with emerging formation of diagnostic horizons
Mollisols	Soils with well-developed A-horizons with high content of organic matter
Oxisols	Soils of the tropics and subtropics with accumulation of Fe- and Al-oxides, losses of Si, and strongly weathered clay minerals, e.g., kaolinite
Spodosols	Acid soils with accumulation of strongly acid organic top layers, leaching of Fe, Al, and organic acids with formation of bleached topsoil horizons
Ultisols	Acid soils of the tropics and subtropics with clay accumulation in lower horizons and very low base saturation
Vertisols	Soils with high content of clay minerals, swelling when moist and shrinking when dry, typical for tropical and subtropical regions with well-expressed wet and dry seasons

6.6 % of the global population. These two soil orders belong to the most productive soils of the globe but are mostly found in temperate regions (compare Fig. 6.3). In the tropics, a high proportion of the population is associated with river terraces (Entisols and Inceptisols) and Ultisols. Ultisols and Oxisols have presented major problems for sustained low-input agricultural production. With increasing knowledge about these soils, more sustainable production became possible (see also Eswaran 1989).

While the Gelisols of the boreal regions have the lowest population density with about 2 persons/km^2, the Andisols, developed on volcanic materials, have the highest with more than 129 persons/km^2, for example, in Central Africa (Rwanda, Burundi, and parts of western Zaire).

In the tropics, Ultisols and Vertisols are extensively used for agricultural production and have population densities in excess of 100 and 120 persons/km^2, respectively. Fragile systems such as those with predominantly Histosols and Aridisols have densities of 21 and 24 persons/km^2, respectively. Although these soils are low in comparison to other soil orders, these densities are threatening the sustainability of the systems in many regions.

The rapidly increasing population in many parts of the tropics has forced the landless poor to move either into urban agglomerations or into marginal fragile ecosystems or to degrade the better resources of their own countries by overuse or inappropriate use.

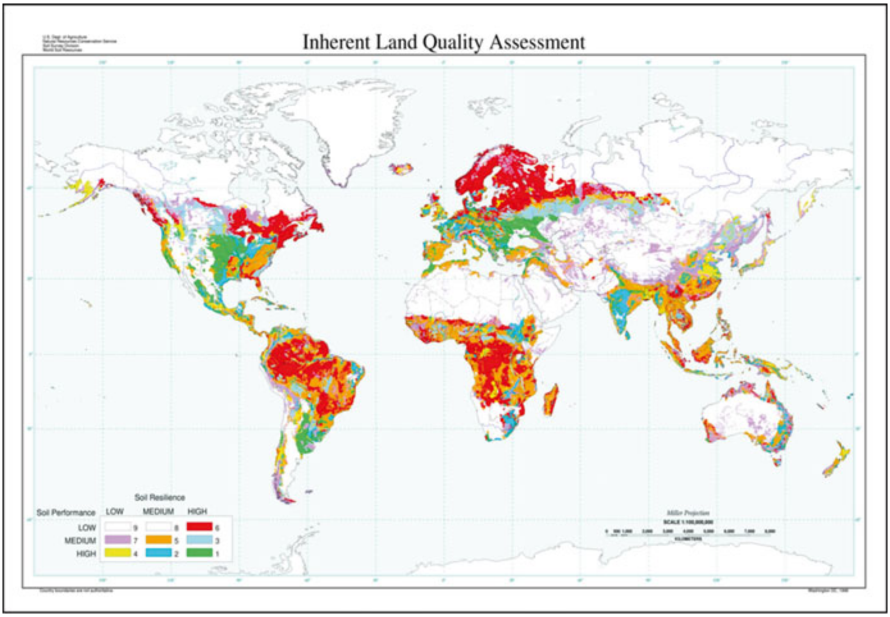

Fig. 6.3 Global map of land quality (Blum and Eswaran 2004)

2.2 Land Quality as the Basis of Soil Use and Management

Land quality is a measure of the ability of land to perform specific functions. It is normal for land to be placed in classes according to the ability to perform the functions outlined earlier. In most systems, the focus of the quality evaluation lays on the performance with respect to biomass production and further on the agricultural component of biomass production (see also Mueller et al. 2010).

For measuring the ability of land and soils to perform specific functions, land and soils are classified according to their capacity to fulfill the abovementioned functions, distinguishing two different intrinsic parameters: their performance, which means their capacity to produce biomass, and their resilience, which means their capacity to return to a new equilibrium after disturbance (see Fig. 6.3).

On the basis of the two intrinsic soil parameters "performance" and "resilience" (see above), Beinroth et al. (2001) produced a nine-class land classification, focusing on agricultural grain production. Table 6.4 presents a summary of the structure of this classification.

The respective areas of the earth occupied by these classes and the population associated with these classes are shown in Table 6.5.

Table 6.4 Properties of the land quality classes for grain production

Land quality class	Properties
I	This is prime land. Soils are highly productive, with few management-related constraints. Soil temperature and moisture conditions are ideal for annual crops. Soil management consists largely of sensible conservation practices to minimize erosion, appropriate fertilization, and use of best available plant materials. Risk for sustainable grain crop production is generally <20 %
II and III	These soils are good and have few problems for sustainable production. For class II soils, however, care must be taken to reduce potential degradation. The lower characteristics of class II soils make them more risky, particularly for low-input grain crop production. Their productivity is however generally very high, and consequently response to management is high. Risk for sustainable grain crop production is generally 20–40 % but can be reduced with good conservation practices
IV, V, and VI	If there is a choice, these soils must not be used for grain crop production, particularly soils belonging to class IV. All three classes of soils require inputs of conservation management if grain production is planned. Lack of plant nutrients is a major constraint, and careful fertilizer management is essential. Soil degradation must be carefully monitored and actions taken to prevent it. Productivity is not high and so low-input farmers must either be discouraged from using these soils or provided with substantial support. Land may be better used for national parks or biodiversity zones and in semiarid areas for rangeland. Risk for sustainable crop production is 40–60 %
VII	These soils may only be used for grain crop production if there is no better-quality land available. They require high levels of management and are not suitable for low-input agricultural production. Their low resilience makes them very prone to degradation. As in class V and VI, biodiversity management is crucial in these areas. Risk for sustainable crop production is 60–80 %
VIII and IX	These soils belong to very fragile ecosystems or are very uneconomical for grain production. They should be retained under their natural state. Some areas may be used for recreational purposes but under very controlled conditions. In class VIII, which is largely confined to tundra and boreal areas, timber harvesting must be done very carefully to prevent ecosystem damage. Class IX is mainly in deserts where biomass production is very low. Risk for sustainable crop production is >80 %

Source: After Beinroth, F.H., Eswaran, H., and Reich, P.F., *Sustaining the Global Farm,* pp. 569–574. Selected papers from the 10th International Soil Conservation Organisation Meeting, 24–29 May 1999, West Lafayette, IN, 2001

Table 6.5 Land area (million km^2) in land quality classes with estimated population (millions) in each class

Land quality	Area		Population	
Class	Million km^2	%	Millions	%
I	3.06	2.38	424	5.9
II	6.40	4.98	993	13.8
III	5.85	4.55	331	4.6
IV	5.08	3.95	820	11.4
V	21.23	16.51	2073	28.8
VI	17.13	13.32	850	11.8
VII	11.58	9.01	797	11.1
VII	11.58	9.01	797	11.1
VIII	21.46	16.69	128	1.8
IX	36.78	28.61	784	10.9

Source: Blum and Eswaran 2004, modified

Class I lands, which have ideal soils located in ideal climates for crop production (e.g., Mollisols) and which are characterized by high productivity and resilience, high response to management, and minimal limitations, occupy only 2.38 % of the global land surface but contribute over 40 % of global food production. The 9.53 % of global land resources in classes II and III have minor limitations (e.g., Alfisols), which are easily corrected and do not pose permanent restrictions to the use of these lands. Most of these lands occur in the temperate regions of the globe, where the climate is moderate, with rare extremes of temperature or rainfall. These soils respond well to management, and the positive effects of appropriate management persist for long periods.

Land quality classes IV, V, and VI (e.g., Ultisols, Oxisols, and Vertisols) cover about 34 % of the global land surface, largely in the tropics, and support over 50 % of the global population. These soils and the environment in which they occur have a range of constraints from high ambient temperatures that reduce germination rates to low nutrient availability that limits biomass production of annual crops. As many of these classes lie within the tropics, where production often is predominantly low input, population is high, and growth rates are higher than in other regions, these lands must be carefully managed and are very vulnerable to degradation if poorly managed.

Class VII lands, occupying a little more than 9 % of the land surface, include shallow soils (e.g., Entisols and Inceptisols), those with high salt concentrations (e.g., Aridisols), and those with high organic matter levels (e.g., Histosols and Spodosols). Shallow soils are normally considered unsuitable for agricultural cropping, and saline soils may be used with specific adaptive crops and cropping practices. The high organic matter peatlands are particularly vulnerable to degradation and permanent loss through drainage.

Class VIII lands occupy almost 17 % of the land surface. They have low temperatures (e.g., Gelisols) and/or steep slopes and are generally considered unsuitable for agriculture. Class IX lands occupy over 28 % of the land surface and are comprised of soils with inadequate moisture to support annual crop production (e.g., Aridisols, shifting sands, rocky lands, and others).

The worldwide distribution of these nine land quality classes is shown in Fig. 6.3. In Table 6.6, the percentage of land area in the main biomes as a function of land quality (Blum and Eswaran 2004) is shown, revealing that only about 35 % of the highly productive soils (classes I–III) occur in the tropics, whereas 65 % occur in regions with boreal, temperate, and Mediterranean type of climates, mostly in the Northern Hemisphere.

Based on Buringh (1985), FAO (1995), and own calculations, about 12 % of the land surface of the world are suitable for food and fiber production, 24 % can be used for grazing, 31 % produce forests, and 33 % are unsuitable for any kind of sustainable use, mainly because of climatic and topographic constraints.

Summarizing it can be stated that food security depends essentially on the 12 % of the land surface with land and soil quality classes I–III, where about 25 % of the world population lives and where all traded food and fiber for the world market is produced.

Table 6.6 Percent of land area in major biomes as a function of land quality

Land quality class (percent of ice-free land surface)										
Biomes	I	II	III	IV	V	VI	VII	VIII	IX	Total
Tundra								15.62		15.62
Boreal			2.03	0.67	0.50	3.05	2.63	1.08	0.09	10.02
Temperate	2.14	2.55	0.70	1.31	4.76	1.66	2.01		0.15	15.29
Mediterranean			0.30	0.15	1.35	0.08	0.65		0.03	2.56
Desert							1.42		28.19	29.61
Tropical	0.25	2.43	1.51	1.83	9.90	8.53	2.31		0.16	26.90
Total	2.38	4.98	4.54	3.96	16.51	13.32	9.02	16.70	28.62	100.00

Source: Blum, W.E.H. and H. Eswaran, 2004, *Journal of Food Science*, 69, 37–42

2.3 Sustainable Land Management: Producing Goods and Services for Global Demands

Sustainable production of goods and services by land management means long-lasting provision of biomass, including food, fodder, and renewable energy, of clean water in the form of groundwater, and of maintaining biodiversity. Moreover, land management must protect open water resources, such as lakes and rivers, against pollution, must control the exchange of climate-relevant trace gases between soils and the atmosphere, and must protect human health against contamination of the food chain.

The goods and services provided by sustainable land management are depicted in Fig. 6.2. Evidently, sustainable land management is a complex task, because numerous competitions exist, e.g., between agricultural production by application of fertilizers and plant protection compounds in the top of the soil and the protection of groundwater underneath, because each drop of rain, falling on the land, has to pass the soil before it becomes groundwater. Moreover, the physical and chemical impacts on soil by agricultural machinery and fertilizer application, respectively, influence the type and quantity of trace gases emitted by soils, such as carbon dioxide (CO_2), methane (CH_4) and dinitrous oxide (N_2O), contributing to climate change.

The management of agricultural soils therefore influences the quantity and the quality of groundwater resources as a second basic need for human life, partly expressed in SDG no. 6. In this sense, SDGs no. 2 and no. 6 are interlinked by land and soil management.

As land management also includes the production of biomass as a basis for the generation of bioenergy, e.g., ethanol from carbohydrates such as from grains, diesel from vegetable oils such as canola and palm oil, and biogas from the fermentation of organic foodstuff or solid burning material such as straw and wood, land and soil management is also linked to a lesser extent to SDG no. 7.

In the following, we will only discuss sustainable land and soil management for biomass production, because sustainability in biomass production will also guarantee the sustainable production of clean groundwater and surface water resources

(SDG no. 6). Moreover, sustainable agricultural and forest production can provide renewable energy for humankind (SDG no. 7).

3 Threats to Land and Soil that May Compromise the Satisfaction of Global Needs

While soils develop in response to a range of environmental conditions, there is a strong concern that the natural functions of soil are increasingly threatened by changes in the environmental context (Scheffer et al. 2001). These changes are frequently human induced or human influenced (Foley et al. 2005); compare also SDG no. 15.

Agricultural activities have a clear impact on global environmental change (Tilman et al. 2001). A number of recent national and international approaches to soil protection have highlighted a list of possible threats to the capacity of the soil to perform its functions. For example, in presenting the case for a European Soil Protection Strategy, the Commission of the European Communities (2002) outlined a series of threats to the sustainable use of soil: (a) soil sealing, (b) erosion, (c) compaction, (d) decline in organic matter, (e) loss of biodiversity, (f) contamination, (g) salinization, and (h) flooding and landslides. Some of these threats related to human activities are summarized in Fig. 6.4.

While the Commission of the European Communities highlighted these threats in the context of Western Europe, they occur globally, their relative importance depending on location and land use. To a degree, these threats arise, because we

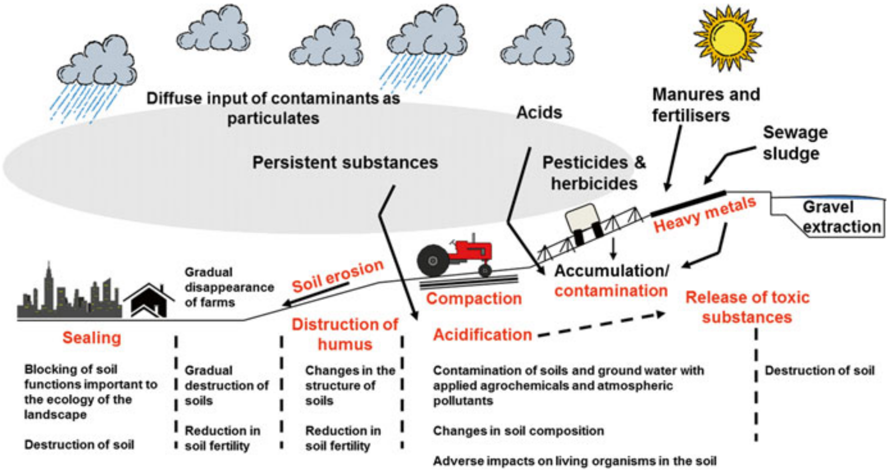

Fig. 6.4 The impact of human activities on soil (JRC "Scientifical and Technical Reports" EUR 23438 EN, Ispra, Italy, 2008. In: Blum, W.E.H., 2008)

expect the soil to perform a range of functions, in some cases many functions at the same time (see Sect. 1.1).

By steadily increasing demands on the soil from these functions, we have often created an unstable system, where the soil becomes less resilient and more vulnerable to these threats (Blum 1988). Consequently, there often is a dramatic reduction in the ability of the soil to perform its normal functions (Lal 2007, 2009; Pretty 2008). In some cases, overemphasis on the performance of one function may result in threats to the ability to perform others (Blum 2005). These threats are increasingly seen as particularly relevant to the biomass production function of soils, including the delivering of biofuels and the generation of freshwater resources.

3.1 *Soil Sealing Through Urbanization, Industrialization, and Transport*

The covering of soil for the infrastructure of modern life, housing, roads, or other land developments is known as soil sealing. When land is sealed, the soil is unable to perform most of its functions, including the absorption of rainwater for infiltration and filtering of contaminating compounds. In addition, sealed areas change superficial water flow pattern, causing flooding and inundations, and increase the fragmentation of biodiversity. Burghardt (2006) noted that the mean daily rate of sealing was 1.29 km^2 during the period 1997–2001 in Germany. Soil sealing is almost irreversible, and there is increasing concern among governments and environmental regulators about this permanent loss of soils and associated loss of ecosystem functions.

The actual extent of global soil sealing can be examined by the view of the earth from space at night (see Fig. 6.5), which clearly shows that most of the high-quality land, expressed by the global distribution of croplands according to Foley et al. (2005) (see Fig. 6.6), is associated with the areas of high levels of urbanization.

High levels of urbanization are visible in North America, Western Europe, and Japan (The Earth Institute 2005), areas which are strongly associated with high-quality land (compare classes I–III in Fig. 6.1). This aspect also becomes visible in the increasing urbanization in the Indian subcontinent and in China. The sealing of the best soil qualities derives from the history of the foundation of settlements, because our ancestors have chosen the best soils for settlement to guarantee the satisfaction of basic needs, such as food, fiber, and water. In the course of time, these first settlements have grown to large urban agglomerations. Any further urban increase therefore results also in the sealing of more prime land. A second effect of sealing is the shift from rural to urban lifestyles resulting in a decrease of biomass production, thus compromising food security.

An estimation of current daily losses of soil through urbanization, industrialization, and transport in the European Union (total surface 4,324,782 km^2) amounts to about 15–20 km^2/day; compare also Prokop et al. (2011). A very rough estimation

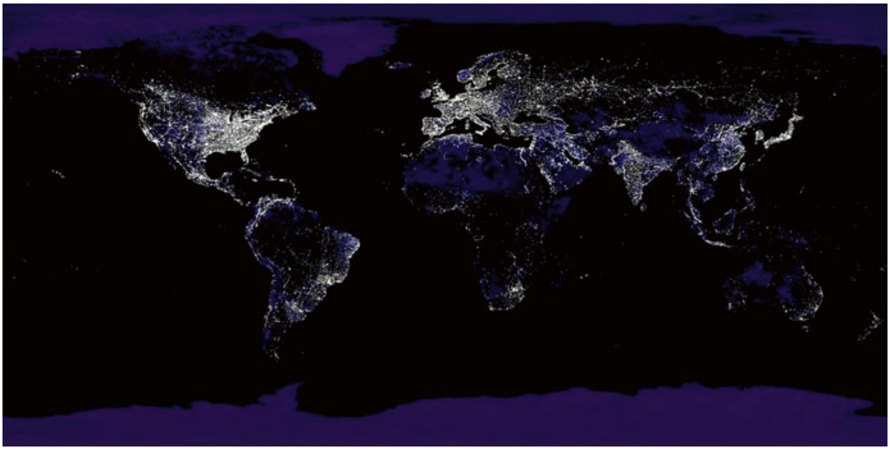

Fig. 6.5 View on earth at nighttime (Courtesy of NASA)

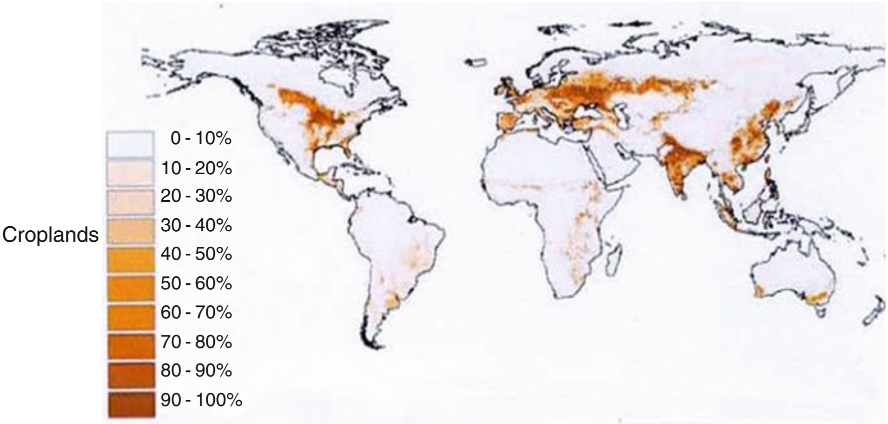

Fig. 6.6 Global distribution of croplands (Foley et al. 2005)

of daily soil losses at the global scale amounts to about 250–300 km^2/day. Therefore, sealing is the most important threat to sustainable agricultural and forest land management.

3.2 Soil Losses Through Land Excavation (for Brick Production)

In many sedimentary areas or large alluvial plains, e.g., in Bangladesh, in the Nile Delta of Egypt between the Damietta and Rosetta branch, and in many other world regions, no solid stones are available for the construction of houses, industrial premises, or other types of building. Therefore, agricultural soils with a higher clay and silt content and without carbonates are excavated down to 3–5 m depths, sometimes even deeper, for the production of bricks, tiles, or other construction materials. In most cases, these are produced near the excavation sites in mobile furnace constructions; see Fig. 6.7. The excavated agricultural soils are irreversibly lost for food and fiber production, because the high groundwater levels in these areas are filling the excavation holes, often with the dimension of several hectares, thus forming small lakes or water ponds (compare Fig. 6.7).

This process is irreversible, because no other soil resources for agricultural production are normally available in the same region. As these areas have one of the highest population densities and one of the highest population growths in the world, problems of food shortage are likely to arise or to happen.

3.3 *Soil Degradation Through Inappropriate Land and Soil Management*

Besides sealing and excavation, additional forms of soil degradation such as erosion, compaction, loss of organic matter, decline in biodiversity, contamination, salinization, desertification, nutrient mining, and floods and landslides are shown in Fig. 6.4; see also Blum (2008).

3.3.1 Erosion

Erosion is a natural geological phenomenon and occurs because of a combination of conditions such as steep slopes, climate (extreme weather conditions), inappropriate land use, poor vegetation cover, and sometimes because of ecological disasters such as tectonic activities or forest fires (Bai et al. 2008). Also intrinsic features of soils such as silty texture and low organic matter content make soils prone to erosion (Boardman and Poesen 2006).

While erosion is a natural process, some activities of humankind may result in a dramatic increase in erosion rates, especially in unsustainable agricultural land use (Lal 2001).

Soil erosion results in the loss of soil functions, at the extreme in the loss of the entire soil. Even the loss of few centimeters of topsoil may often have a disproportionally large impact on the soil ability to sustain high levels of biomass production (Den Biggelar et al. 2003). Lal (2003, 2005) also highlighted the close link between the erosional loss of organically enriched topsoil and thus the possible impact on the global carbon budget. Moreover, there are additional impacts, because the soil is transported to watercourses, adding contaminants and increasing the turbidity of the water with further environmental damage through its deposition downstream.

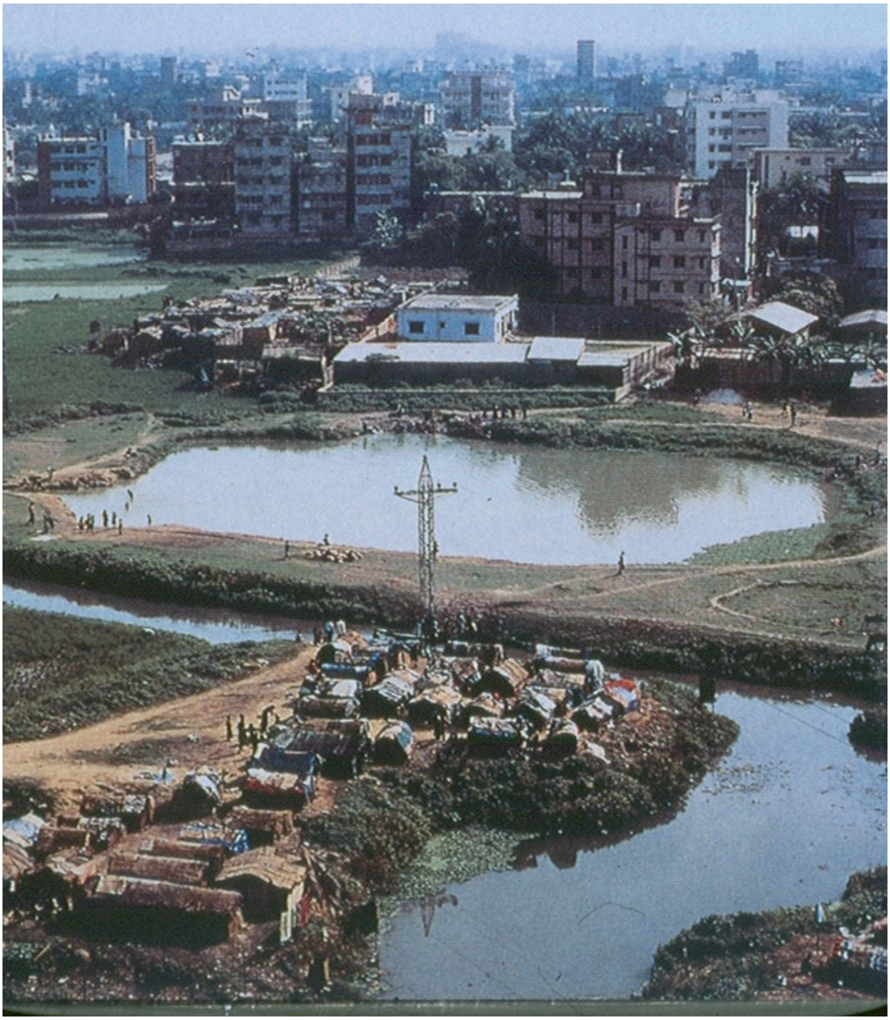

Fig. 6.7 Excavation of agricultural soils for brick production near Dhaka/Bangladesh (in the foreground, excavation ponds and brick production in mobile furnaces; in the background, houses constructed with bricks)

3.3.2 Compaction

Soil compaction occurs on agricultural land when soil is subject to mechanical pressure through the use of heavy machinery or overgrazing, especially in wet soil conditions (Horn and Peth 2011). It has long been recognized as a potential problem in agricultural systems. In addition to recognizing the need to avoid compaction by minimizing traffic when soils are wet and more vulnerable to damage, declines in soil organic matter levels can be observed. These were a possible contributory factor to the increased vulnerability to compaction. In sensitive areas, walking tourism (hiking) and skiing also contribute to the problem, and in construction sites, compaction is a common occurrence. Compaction reduces the pore space between soil particles, and the soil partially or fully loses its capacity to absorb water. Compaction of deeper soil layers is difficult to reverse (Horn et al. 2000). The overall deterioration in soil structure caused by compaction restricts root growth, water storage capacity, and biological activity and stability and significantly reduces fertility and biomass production (Horn et al. 2006; Clarke et al. 2008). Moreover, when heavy rainfall occurs, water can no longer easily infiltrate the soil, which may generate surface water runoff, causing erosion or even flooding and inundation.

Possibly more significantly though, water that runs off will not replenish the soil and near-surface storage of water. Near-surface stored water is essential to sustain plant growth during rainless periods in most agricultural systems.

3.3.3 Decline in Organic Matter

Soil organic matter is composed of organic material (plant root remains, leaves, and other plant material, dead fauna, and excrements), living organisms (bacteria, fungi, earthworms, and other soil biota), and humus. In natural systems, organic material is constantly added to the soil and decomposed. During this decomposition, plant nutrients are released and often rapidly taken up by the plants, thus forming an almost closed cycle. Additionally, carbon is released to the atmosphere as $CO_{2,}$ which is then recaptured through the process of photosynthesis.

Organic matter plays a central role in maintaining key soil functions and is a major determinant of the resistance of soil to erosion and underlying soil fertility (Lal 2002). It contributes to the aggregation of soil particles and the physical and chemical buffering capacity of the soil, thus contributing to limit the diffusion of pollution from soil to water. It is widely recognized that farming and forestry practices have an important impact on soil organic matter; see also Pulleman et al. (2000) and Sonneveld et al. (2002).

Despite the recognized importance of maintaining the organic matter content of soil, there is evidence that, with a shift in the last half century toward greater specialization and cereal monoculture, particularly in temperate regions, losses of soil organic matter through natural decomposition are often not completely replaced.

Specialization in farming has led to the separation of livestock from arable production, so that rotational practices, which were important in the past in maintaining soil organic matter content, are often no longer a feature of the farming system. There has also been concern that recent shifts in climate may have further contributed to changes in soil organic matter levels (Bellamy et al. 2005; see also Sect. 4.3).

The buildup of organic matter in soils is a slow process, much slower than the decline in organic matter observed as a result of poor management. However, these declines can be halted or even reversed by land management practices such as conservation tillage, no-tillage cropping techniques, organic farming, permanent grassland, cover crops, and manuring and mulching with green legumes, farmyard manure, and compost.

A number of authors have stated significant accumulations of carbon in the soil, following the adoption of conservation tillage practices. Fuentes et al. (2010) compared soil organic carbon contents following 16 years of conventional tillage and zero tillage in the central highlands of Mexico and found levels of organic matter significantly higher in the zero-tillage sites. They also noted that the retention of organic residues on site strongly influenced the soil carbon levels. Sombrero and de Benito (2010), reporting a study from Castile-León in Spain, noted increases in soil carbon levels and soil structural stability under minimum- or no-tillage systems. They also noted that the levels of soil carbon were affected by soil type, crop type, crop rotation, and the quantity and quality of crop residues left on the soil surface. These techniques, in addition to addressing the issue of soil organic matter, have also been shown to be effective in preventing erosion, increasing fertility, and enhancing soil biodiversity.

In many smallholder farming systems in the tropics and subtropics, soil organic matter plays a significant role in the provision of nutrients for crop production. Traditional practices frequently involve periods of fallow, when no crop production takes place, and soil amendments with crop and plant residues and manures, practices which increase or at least maintain the level of organic matter. Increasing pressure on land through increasing population and losses of land through sealing and erosion has often reduced the fallow period and resulted in lower levels of organic matter recycling. Reductions in the level of organic matter in soils with lower capacity to produce biomass and increased vulnerability often result in erosion and compaction, which reduce the biomass production capacity of the soil.

Soil organic carbon also plays a major role in the global carbon cycle. Recent studies (e.g., Post and Kwon 2000; Guo and Gifford 2002; Lal 2010) have emphasized the important role of the soil organic carbon pool in the context of global carbon fluxes and have raised awareness of the role of land use management practices in both maintaining soil carbon stocks and potentially increasing the sequestration of carbon in the soil pool.

3.3.4 Decline in Soil Biodiversity

Soil is the largest gene reserve on earth and a habitat for a huge variety of living organisms. Because of the interactions of the soil-forming factors such as geology, climate, vegetation cover, topography, and others, there is an enormous diversity in the nature of soils and of soil organisms (Bardgett et al. 2005; Gardi and Jefferey 2009). Our knowledge of the organisms found in the soil is incomplete. We have some knowledge of the relative magnitude but very limited knowledge of the nature and function of soil biota, especially of microorganisms (e.g., see Pimentel et al. 2006). Soil bacteria, fungi, protozoa, and other microorganisms play an essential role in maintaining the physical, chemical, and especially biochemical properties needed for soil fertility (Barrios 2007; Brussaard et al. 2007). Larger organisms such as worms, snails, and small arthropods contribute to reducing the size of organic matter remains, which are further degraded by microorganisms, and carry it to deeper layers of soil, where it is more stable. Furthermore, soil organisms themselves serve as reservoirs of nutrients, suppress external pathogens, and break down organic pollutants into simpler, often less harmful components (Decaëns et al. 2006; Turbé et al. 2010).

The interrelationships and interdependences among species are complex. The loss of a single species may have a cascading effect, because of this interdependence, resulting in a further loss of species and associated functions (Pimentel et al. 2006).

Reductions in soil biodiversity make soils more vulnerable to other degradation processes and frequently reduce their ability to perform many ecosystem functions (Hunt and Wall 2002; Matson et al. 1997). As soil biodiversity is intimately interlinked with the aboveground biodiversity, both interact with many soil and further environmental functions and are often used as an indicator of the state of soil health or that of a broader environmental system (e.g., Harris and Bezdicek 1994; Chapin et al. 2000).

Although the complexity of soil biodiversity dynamics is not yet fully understood, there is evidence that biological activity in soils is largely dependent on the occurrence of appropriate levels and quality of organic matter.

3.3.5 Contamination

The introduction of contaminants in the soil may result in damage to, or loss of, individual or several functions of soils and the possible contamination of groundwater and surface water resources. The occurrence of contaminants in soils above certain levels entails multiple negative consequences for the food chain and thus for human health and for all types of ecosystems and other natural resources. To assess the potential impact of soil contaminants, not only their concentration but also their environmental behavior and exposure mechanisms for human and ecosystem health have to be taken into account. A distinction often is made between soil contamination originating from clearly confined sources (local or point source contamination) and that one caused by diffuse sources.

The report of the Technical Working Group on Soil Contamination (Van Camp et al. 2004), established under the European Commission's Thematic Strategy for Soil Protection, provides a comprehensive summary of the sources and distribution of contaminated soils in Europe.

Local (or point source) contamination is generally associated with mining, industrial sites, waste landfills, and other facilities, both during their operation and after closure. These activities can pose risks to both soil and water. In mining, the risk is associated with the storage or disposal of tailings, acid mine drainage, and the use of specific chemical reagents. Industrial facilities can also be a major source of local contamination. In some cases, the contamination may persist for many years.

Diffuse pollution is generally associated with atmospheric deposition, certain farming practices, and inadequate waste and wastewater recycling and treatment. Contaminants released as emissions from industry, traffic, and agriculture cause many of the diffuse atmospheric pollution sources.

The deposition of airborne pollutants releases acidifying contaminants (e.g., SO_2, NO_x), metals (e.g., cadmium, lead, arsenic, and mercury), and a range of organic compounds (e.g., dioxins, PCBs, polycyclic aromatic hydrocarbons) into soils.

In addition to the soil–atmosphere links, there are also strong links between the soil and the hydrosphere. In a study from northern France, Gutierrez and Baran (2009) noted the importance of considering the impact of diffuse pollution, which may arise from the application of agrochemicals on water resources. Because of the often complex nature of the linkages between the soil and underlying hydrological systems, the consequences of this pollution may not be reflected in the quality of the groundwater for some time. It is important therefore to consider the nature of these linkages, when attempts at managements to prevent further contamination and when remediation of contaminated soils and water resources are being planted.

Soil contamination can impact food production in two ways. The first direct impact is the reduction of the productive capacity of the soil, because the contaminants inhibit growth. A second impact on food production is due to food that may be unfit for human consumption because of an uptake of contaminants during growth. The increased urbanization and industrialization mentioned previously, if allowed to proceed without careful planning and control, have the potential to produce soil contamination and further impact on global food production (Blum 1998).

3.3.6 Salinization

Salinization is the accumulation of soluble salts of principally sodium, magnesium, and calcium in soils to the extent that crop production is severely reduced. This process often is associated with inappropriate irrigation practices as irrigation water will contain variable amounts of salts, in particular in regions where low rainfall, high evapotranspiration rates, or soil textural characteristics impede the washing out of the salts, which subsequently build up surface layers in the soil (Singh 2009). In coastal areas, salinization can also be associated with groundwater overexploitation, leading to a lower water table, thus triggering the intrusion of saline marine water.

With the increasing demand for food from a growing global population and changes in the diet associated with increasing wealth, marginal land is frequently brought into agricultural production. Where insufficient stored water is the reason for the marginalization of the land, irrigation is often the immediate option for bringing the land into food production.

Without careful management of both the water resources used for irrigation and the soil being irrigated under the mentioned climatic and overall ecological conditions, salinization will increase in the future, especially in view of the quickly decreasing global resources of freshwater and the actual worldwide extension of irrigated land for satisfying the demands of food for the growing world population. This will be particularly problematic, where scarce high-quality water resources and the conflicting demands from human consumption result in lower-quality, often saline water, being the only resource available for irrigating crops (e.g., Galvani 2007).

3.3.7 Desertification

Desertification is a complex process of land degradation through natural and human-induced impacts (e.g., as a result of environmental responses to climate change). It is expressed in terms of increased periods of droughts and overuse of natural resources, especially vegetation cover, by grazing or fuel wood collection, with subsequent soil degradation and soil losses, including salinization (Anjum et al. 2010). An example for South Africa is given by Stringer and Reed (2007).

Land prone to desertification was normally not used as cropland for food production but was always an important part of the agriculturally productive areas and often used as pastures, for example, by nomads. The loss of these areas by desertification increases the pressure on still-productive land and soils for food production and may even cause social conflicts (Blum 2009). Dregne (1998) estimated that 3,592 billion ha of land had been affected by desertification. Eswaran et al. (2001) estimated that a "desertification tension zone" affects a total land area of about 4.23 billion ha, of which 1.17 billion is in areas with high population density (<41 persons/km^2). Bai et al. (2008) estimated that land degradation affected 3.5 billion ha or approximately 24 % of the land surface of the earth. Reynolds et al. (2007) present more sustainable approaches in the use of dry lands at a global level in response to desertification pressures.

3.3.8 Soil Nutrient Mining

While not mentioned as a threat in the European context or in any of the other soil protection policies recently developed, soil nutrient mining is possibly one of the most significant threats to food production in large parts of the tropics. Agricultural production in much of Africa is threatened by nutrient mining (Hartemink 1997; De Jager et al. 2001). The context of agricultural production in much of the continent is one of fragile ecosystems, low inherent soil fertility, and less use of modern inputs such as mineral fertilizers, plant protection products, and improved crop varieties. The traditional practice in Africa, and in particular sub-Saharan Africa, is one of fallow systems, where soil is left uncultivated to allow "recovery." Increasing pressure on land from both rising population and, in some countries, exclusion of indigenous populations from parts of the landscape through land grabbing has resulted in a reduction in the length of fallow periods and in some cases their removal. This trend, particularly where no or at best very low levels of fertilizer are applied, has often resulted in the depletion or "mining" of the soil nutrient store. With reduced nutrient levels, the soils are less productive, and to maintain overall levels of food production, the populations seek to exploit marginal lands often with lower inherent fertility and other constraints on crop production, thus degrading land with significant ecological value.

These declining fertility levels in African soils as a result of nutrient mining have resulted in decreased crop yields and per capita food production with a reduction in food security and in the mid- to long term are likely to be a key initiator of broader land degradation (Henao and Baanante 2006).

Nutrient balances which consider the inputs and outputs from the system have been used to estimate the magnitude and extent of nutrient mining. Inputs are fertilizers, organic residues, manures, nitrogen fixation, and sedimentation. Outputs are through crop uptake and export, erosion, leaching, and volatilization.

During the period 2002–2004, 85 % of African agricultural land (1.85 million km^2) had annual nutrient mining rates over 35 kg (N, P, and K)/ha and 40 % had annual rates greater than 60 kg/ha. There are of course wide variations in the observed rates across the continent, with an annual rate of 8 kg/ha in Egypt and 88 kg/ha in Somalia.

Unless policies are introduced to limit this "mining" through, this degradation process is likely to continue. Support for agro inputs together with associated conservation practices and improvements in the competitive environments for African farmers are necessary, so that they are able to embrace an element of forward planning with indicative progress for their produce. In some areas, a key change is to establish farmers' tenure for the land that they farm. Where there is no tenure, there is no incentive to manage the soil sustainably and for the long term. Short-term management will encourage nutrient mining.

3.3.9 Floods and Landslides

Floods and landslides are mainly natural hazards, intimately related to soil and land management practices, although their impact is often exacerbated by unusual environmental conditions. Landslides have a predominantly local impact on food production, although they may temporarily impact food distribution through the disruption of communication networks. Floods may be both local, impacting a few hectares, or in extreme cases nationwide, impacting thousands of square kilometers. Flooding may cause soil erosion, with the loss of soil, seed, and, in extreme cases, crops, and contamination with sediments. In addition to the damage to soil and the natural environment, there are often major impacts on human activities and human lives, damage to buildings and infrastructures, and loss of agricultural land, too. Floods and landslides are not a threat to soils in the same manner as the threats already listed. In some cases however, floods can partly result from soils not performing their role of controlling the water cycle due to compaction or sealing. Floods and landslides may also be favored by erosion of the soil cover, often caused by deforestation or by land abandonment.

4 Global Change Threatening Food Security and Water Supply

4.1 Global Change: An Introduction

Besides the threats to soil directly endangering food production and freshwater supply through local or regional processes, such as soil losses (e.g., sealing and excavation), as well as through soil degradation through erosion, compaction, decline in soil organic matter, decline in soil biodiversity, contamination, salinization, desertification, nutrient mining, and floods and landslides, there are global processes threatening food and water security. These are indirectly linked to the provision of goods and services by land and soil, such as population increase, migration from rural into urban areas, and change in lifestyle and food habits, which increase the demand for space and food and at the same time threaten the basis of food production. Moreover, through an increasing demand for and use of energy and the destruction of natural resources for the extension of food and fiber production, additional impacts on climate change occur, which add to the already existing problems through the use of fossil energy. The tendency to increase production of biofuels, which competes for space and energy with food production, is a further threat to food security, in addition to the existing economic crisis and the emerging economic procedures on food production and marketing, such as land grabbing, hedging, and the use of derivatives in food trading. These developments and processes at a worldwide level will be discussed under global change.

4.2 World Population Increase, Migration, and Changes in Lifestyle and Food Habits

The world population increases by about 80 million per year, with very unequal distribution worldwide (IIASA 2007; Lutz et al. 2008). About 70 % occur in sub-Saharan Africa, South and Southeast Asia, and Central and South America. New scenarios for the development of the world population in the context of sustainable development were presented by Lutz et al. (2014).

Even with an increase in food production of more than 12 % since 1990, the global undernourished population increased by about 9 % (Barrett 2010). Lal (2010) noted that the number of food-insecure people rose from 854 million in 2007 to about 1020 million in 2009, also due to changes in market conditions and food pricing (see also FAO 2008; IFPRI 2008). According to FAOSTAT (2011), the number of people suffering hunger declined to about 926 million in 2010. All these figures include only people who are protein/calorie malnourished and do not include those who are iron malnourished (about two billion) and iodine malnourished (about 750 million) or show other specific nutritional deficiencies (WHO 2000). Pimentel esti-

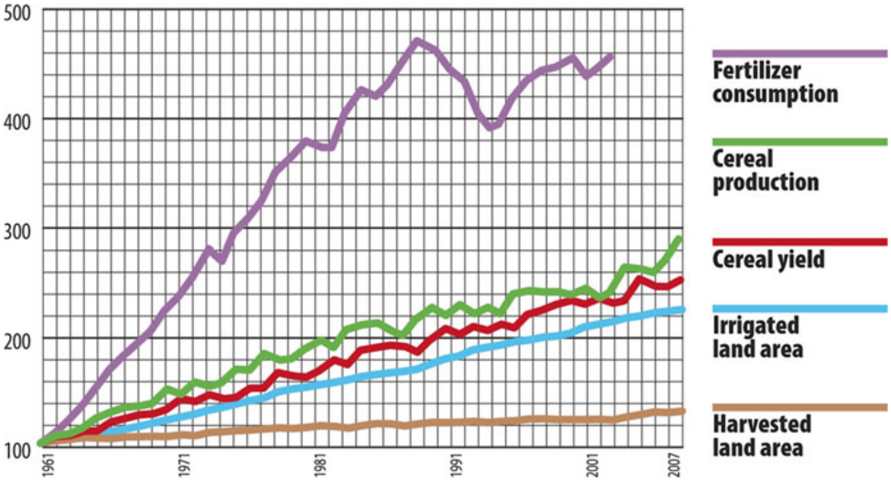

Fig. 6.8 Indicators of global agricultural production intensification, 1961–2007, Index (1961 = 100). FAOSTAT, (2011)

mates that in total about 60 % of the world population is malnourished (personal communication based on FAO and WHO data).

In the second half of the twentieth century, increases in global food production of nearly 250 % matched increases in population, from about 2.5 billion in 1950 to about 6 billion in 2000 (Blum and Eswaran 2004; Godfray et al. 2010), mainly through the success of the "green revolution" (Borlaug 2007) but also the input of an enormous amount of fossil energy in the form of fertilizers and plant protection compounds; see Fig. 6.8 (FAOSTAT 2011). However, in the final years of the twentieth century, population growth began to outstrip productivity increases. The per capita food production therefore showed a slight decrease over the time period. Moreover, in some areas (e.g., Africa), the green revolution had little impact (Sanchez and Swaminathan 2005), in part because of nutrient-poor soils and limited access to fertilizers, plant protection products, and insufficient agricultural tools (Scherr 1999). St. Clair and Lynch (2010) reported that the global demand for food is expected to increase between twofold and fivefold in the period 1990–2030. At the same time, the per capita area for land dedicated to food production, currently about 0.27 ha, continues to decrease because of population growth as well as increasing soil losses through urbanization and land and soil degradation; see also Satterthwaite et al. (2010).

Lele (2010) noted that the main focus for poverty reduction is on Africa and Asia, where 97 % of the world's food insecure are found (see also Rosegrant and Cline 2003). The food price hike in 2008 (Piesse and Thirtle 2009) exacerbated the problem of food shortages, with many people in Africa and Asia not having the buying power to purchase food. Bai et al. (2008) note that at the same time, the growth in cereal yields expected for much of the second half of the twentieth century has slowed and that the climatic shifts predicted by the Intergovernmental Panel on

Climate Change may result further in a 20–40 % drop in cereal yields, mostly in Africa and Asia. In addition, by 2050, there will be about 2.3 billion more people, which means that removing this poverty stress and feeding the additional population will require a 70 % increase in cereal yields and a doubling or more of the output of countries in development. Even under an increase of more than 200 % in grain production during the last 50 years, the land devoted to arable agriculture has increased by less than 10 % (Godfray et al. 2010). It is likely that, by 2050, we shall need 70–100 % more food to feed the estimated global population of nine billion (Royal Society of London 2009).

Will there be new land for food production? The competition for land from other uses, especially biofuel production, makes this increasingly unlikely. The recent awareness of the need to protect biodiversity and to retain the goods and services provided by natural ecosystems makes substantial increases in the area of land devoted to agriculture very unlikely.

Besides the increase in world population, the migration of about 80–100 million per year from rural to urban areas (United Nations 2004) is driving urbanization and results in further sealing and degradation of productive land, as can be seen in many slum areas around urban centers in Africa, Asia, and Latin America.

Moreover, the worldwide increasing demand for animal products, especially protein in the form of meat but also eggs and milk (FAOSTAT 2011; Godfray et al. 2010), is threatening food security because of the consumption of grain in animal husbandry. For the production of 1 kg of chicken meat, about 2–3 kg of grain is needed; for 1 kg of pork, about 4–6 kg of grain; and for 1 kg of beef, about 7–10 kg of grain (Zhou et al. 2008). This means that large quantities of vegetable food are lost for human consumption, as they are used as animal feed without consideration of the additional environmental impacts (De Vries and de Boer 2010; Xiong et al. 2008).

4.3 Climate Change Threatening Food Security

Climate change is influencing all biological processes in terrestrial and aquatic ecosystems and thus threatening food production in different ways. More frequent extreme weather events cause water and wind erosion, floods and landslides, desertification, and salinization, which in turn increase soil losses and degradation (Alley et al. 2003; Haron and Dragovich 2010). Plant growth is stressed through extreme variations between dry and wet conditions, especially during longer droughts. In addition, there is an increasing lack of freshwater for irrigation and competition for water used in biofuel production, industry, and households (Rosegrant and Cai 2002). Schmidhuber and Tubiello (2007) discussed the complexity of climate change impact on food security at the global level (see also IPCC 2014). Lavalle et al. (2009) investigated the impact of climate change on agriculture and forestry in Europe. A case study for Mali was published by Butt et al. (2005).

Moreover, food and biofuel production are exacerbating climate change through increasing deforestation for agricultural land use, urbanization, industrialization, and transport, thus reducing carbon sequestration through soils. Intensive agricultural production of food and biofuels increases the output of greenhouse gases, such as methane (CH_4) and dinitrous oxide (N_2O), which have a much greater effect on climate change than CO_2 from soils and animals (see also Blum et al. 2010).

The actual increase in water-deficient regions, for example, in the Near East, the Mediterranean, and other world regions, is already playing a decisive role in food production through irrigation (IWMI 2007; see also FAOSTAT 2011).

On the other hand, the increase in temperature, especially in the northern regions of America, Asia, and Europe that have sufficient freshwater resources, may partly compensate for the losses of food production in water-insecure regions and those with extreme soil losses and soil degradation.

4.4 Changes in World Economy with Emerging Economic Trends in Food Production and Marketing

In the first years of the twenty-first century, when the world economic crises started, new economic concepts in food production and marketing emerged or were realized (Piesse and Thirtle 2009). For the first time, food became subject of widespread speculation through derivative transactions on global and regional food markets (Garcia and Leuthold 2004; Williams 2001), causing a strong volatilization of prices and problems of food availability, especially for the poor; see also IFPRI (2008). Land grabbing (i.e., the purchase or rent of large territories for food or biofuel production, especially in countries in development) also increased considerably. More than three million ha of land were grabbed in Africa, Asia, and Latin America in the years 2006–2009, for food supplies only (von Braun and Meinzen-Dick 2009).

Whereas derivative transactions are a form of economic speculation with agricultural products, especially food, land grabbing can totally change the agricultural and rural landscapes of countries, as described by Adesina (2010) for Africa. Moreover, direct problems with soil fertility are to be expected, especially when food and biofuel production is maximized to make maximum profit out of purchased or rented land (Robertson and Pinstrup-Andersen 2010; Davis et al. 2014). Land grabbing is a clear sign that many industrialized countries and international enterprises have recognized that land cannot be increased, and due to constant losses of productive land in their own environment and increasing demands for food and energy at the local and global levels, secured land in foreign countries and regions for sustaining food and biofuel production has become an important asset.

4.5 Food Security and Biofuel Production: A Competition for Space, Energy, and Water

Due to the steadily increasing prices for fossil energy in the form of oil and gas, the production of biofuel in gaseous form as biogas, in liquid form as biodiesel or ethanol, and in solid form such as straw and wood has become economically interesting, especially in cases where financial subsidies are granted in view of the contribution to the mitigation of climate change by the use of biofuels. Goldemberg and Guardabassi (2009) discussed the advantages and disadvantages of biofuel products from carbohydrates (see also Demibras 2007; OECD 2007; Pimentel and Pimentel 2007). Pimentel (2010) discussed the environmental impacts of cellulosic ethanol production.

In many parts of the world, especially in Asia and Latin America, natural vegetation cover (e.g., forests) is destroyed in order to gain new surfaces for biofuel production (Fargione et al. 2008), mainly sugarcane and oil-producing plants. The trilemma between food security, energy security, and environmental security was highlighted by Popp (2010).

In view of the constantly decreasing surface for food production, due to urbanization, industrialization, and transport, and soil losses and degradation through erosion and other forms, biofuel production is in strong competition with food production and therefore with food security, at least in the medium to long run (Pimentel et al. 2009; Tilman et al. 2009). Moreover, there are clear indications that agricultural biofuel production is endangering soil quality, because of the complete removal of organic matter and the return of insufficient organic matter residues to the soil for maintaining the organic matter status of soils and biodiversity (Cruse et al. 2010; Lal and Stewart 2010). Further forms of possible soil degradation can be distinguished (Blum et al. 2010).

Further competition exists for water. In many regions of the globe (e.g., in the Mediterranean basin), there is already insufficient water for food production (Bernades 2008).

5 Conclusions and Outlook

The large increase in food production in the second half of the last century, mainly through the “green revolution” and further positive developments, especially the use of fertilizers and plant protection products, could not prevent the situation that today nearly one billion people live with hunger, mostly because of lack of access to food. In total, about four billion people can be considered malnourished, due to further specific nutritive deficiencies.

The sustainable production and availability of food are also increasingly threatened by impacts deriving from human activities, especially changing forms of land use at local and global scales. Most critical are soil losses through sealing by urbanization, industrialization, and transport, probably the most important threat to food security at all, but also erosion by water and wind and further severe forms of soil degradation, such as loss of organic matter, contamination, loss of soil biodiversity, compaction, salinization, nutrient mining, desertification, and flooding, endanger food security.

In addition, the decrease in productive agricultural area and the degradation of the remaining productive surfaces are not the only threat to food security. There is an annual increase in the world population of about 80 million and a migration of 80–100 million per year from rural to urban areas, where people depend on food markets without being able to produce their own food any longer.

Climate change as well is threatening food security directly with increasing losses and degradation of soil, mainly through extreme events. In many regions, a decrease of freshwater resources is threatening rain-fed and irrigation agriculture. Meanwhile, there is a serious competition for space, energy, and water emerging from biofuel production and a concomitant increase in demand for food and fiber on local and world food markets.

New economic concepts and speculation on food markets (e.g., in form of derivative transactions) can hamper access to food through high volatilization of food prices. The decreasing availability of productive agricultural land has led to land grabbing, mostly in developing countries in Africa, Asia, and Latin America, threatening land and soil quality.

All this underlines that we are still far away from reaching SDG no. 2, "End hunger, achieve food security and improved nutrition and promote sustainable agriculture," or SDG no. 6 in ensuring availability of water for all or SDG no. 7 by ensuring access to energy for all. Without new approaches in biomass production, especially food production at local and worldwide levels, protecting concomitantly the groundwater resources against contamination and producing enough biomass for sustaining local and global energy needs, it has to be expected that within one or two decades, food and water shortage will severely further threaten millions of people and increase hunger, especially in countries in development.

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Chapter 7
Implications of the Nexus Approach When Assessing Water and Soil Quality as a Function of Solid and Liquid Waste Management

Johan Bouma

Abstract The Nexus approach is valuable when screening the overwhelming number of publications on water, waste, and soils by: (1) focusing on linkages and trade-offs between the three constituting elements, (2) being a source for inter- and transdisciplinary research, and (3) facilitating communication. To be most effective, the elements should have a comparable degree of detail, and linkages should be expressed in terms of ecosystem services to cover impacts beyond the local. Solid and liquid wastes are well defined in terms of properties, generation, and characterization processes. Regional water regimes can be expressed by widely available hydrological models in which, however, the soil component is usually poorly represented. Unsaturated flow in the soil is crucial for the integration of solid waste (compost), increasing the organic content, and for disposal and purification of liquid waste, the latter either on the surface or in subsurface seepage beds for on-site waste disposal from septic tanks. Every soil has a characteristically different unsaturated flow regime that is insufficiently known at this time. Generation of compost from urban waste is increasing worldwide, offering potential opportunities for soil quality improvement, and successful application of liquid waste to soil cannot only benefit agriculture through irrigation but is also a contribution to groundwater supply and erosion control.

1 Introduction

Clean water is essential for life on Earth, and healthy soil is crucial for natural plant life and food production for the world's growing population that is likely to number more than nine billion by 2050. The interlinkages of these two key elements of the biosphere are through hydrological and geochemical processes that are sometimes altered as a result of human activities (such as inappropriate waste management).

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H. Hettiarachchi, R. Ardakanian (eds.), *Environmental Resource Management and the Nexus Approach*, DOI 10.1007/978-3-319-28593-1_7

In recent years, cooperation between soil scientists, particularly pedologists, and hydrologists has been cemented in hydropedology (e.g., Lin et al. 2006; Bouma 2006; Bradeau and Mohtar 2014).

Water quality has become a major concern worldwide due to increasing pollution of surface water and groundwater resources especially in developing countries. Soil pollution, agricultural waste runoff, inappropriate solid waste management, reuse of insufficiently or untreated wastewater for irrigation, and open defecation due to lack of sanitation are among the major sources of water pollution. As the world becomes more industrialized, urbanization and changes in lifestyle, both in developed and developing countries, are bound to lead to generation of more solid and liquid waste, increasing the potential for soil and water pollution due to leaching of organic compounds and other pollutants such as heavy metals. Even more menacing, in many developing countries, direct discharge of waste into land and water bodies is a common practice. Another major concern for water quality is related to agricultural practices due to surface runoff and seepage to groundwater of excess fertilizers and biocides.

Soil pollution, resulting from unsustainable land use, application of excess fertilizers or biocides, and inappropriate waste disposal that may discharge heavy metals and toxic organic substances onto the soil, is also a growing concern. Hence, to protect water quality, it is needed to improve wastewater, waste, and soil management in a holistic way based on the Nexus approach.

The description presented above demonstrates the overwhelming complexity of the water-soil-waste Nexus. There are many different soils; the complex water cycle is fed by precipitation which feeds surface water and groundwater in a highly dynamic landscape context, including a large volume of water in the unsaturated zone of the soil (“green water”; see Sect. 6).

There are many types of wastes as well. The number of combinations of the three elements of the Nexus is therefore infinite: each specific case is unique. A key question for any Nexus is therefore how to realistically generalize and formulate general principles to allow the creation of a meaningful Nexus approach. This needs to take into account trade-offs between often contrasting demands for the separate, competing elements requiring an inter- and transdisciplinary research approach that defines “options,” from which choices have to be made, rather than non-existing unique “solutions” (e.g., Bouma 2010; Mohtar and Daher 2014). This position paper deals with the waste-soil-water Nexus, which is, of course, part of much broader environmental and societal issues dealing with food and energy security, biodiversity loss, and climate change. Lal (2015) has provided an excellent overview of links with these broader issues.

The Nexus concept is all about linking, and it can be helpful to devise a general scheme that can be used to structure studies on the water-soil-waste Nexus. Such a scheme cannot only be helpful to guide future research but can also function to more efficiently communicate results of earlier studies.

This position paper will therefore not try to systemize or classify the overwhelming number of studies that have been made about the three elements of the water-soil-waste Nexus but will first discuss a possible scheme to frame such studies, focusing on what makes the Nexus concept attractive for each of the three constituting elements. So rather than discuss the issues as separate entities, we will consider waste in terms of what it means and can mean for soil and water quality. We will consider soil in terms of how its functions can be improved by waste and how water quality is affected by soil properties and by the type of waste being considered. Next, some selected integrated studies and their requirements will be reviewed, including management practices. Finally, attention will briefly be paid to the "people" and "policy" aspects related to the Nexus. In the so-called developed world, an increasing number of citizens are slowly getting used to the idea of waste as "a resource out of place." Thus, application of waste to soil and water is acceptable in principle, when it is done in the right way. This, of course, needs to be well documented. But waste still has a quite negative even emotional connotation in both the developed and developing world that has to be taken into account when devising innovative waste management schemes. A purely technical approach is not likely to produce convincing results in practice.

2 "How" to Connect "What" in the Water-Soil-Waste Nexus

The central Nexus question starts with the origin and character of the liquid or solid waste. What is its quality and volume? Is the source permanent, periodic, or restricted to a one-time event? As discussed above, when discharged directly into surface water, there is bound to be a water quality problem, except when the released quantity is relatively low and when the surface water flows rapidly, like in a river or a tidal area. This follows the old adagium: "the solution to pollution is dilution." Which components in the waste can potentially be important for the quality of soil and water? Which components may be harmful?

Realizing that the soil can improve the quality of percolating wastewater (as we will discuss later in more detail) or can absorb and incorporate solid waste, we should next consider soils that can play a role in accepting the waste. Taking into account climate data including precipitation patterns, the question can be raised whether or not soils can accept a certain quantity of wastewater or solid waste without adversely affecting its functions. More positively, can waste or wastewater improve the soil functions?

This finally introduces the water aspect which is partly integrated with the soil: (1) water as carrier of liquid waste, (2) wastewater being purified as it moves through the soil, and (3) water defining, together with the temperature and aeration regime of any given soil, the potential to incorporate solid waste, without, again, adversely affecting its functions. Considering this analysis, we suggest to follow the sequence waste-soil-water when characterizing the Nexus, as considered here. This is arbitrary. One could also start by defining the soil-water dynamics and then adding the waste aspect. In both cases, soil and water are highly integrated, as expressed by hydropedology. This relates, of course, mainly to the unsaturated zone.

Traditional hydrology as such is important when dealing with flow patterns of groundwater and surface water.

But before discussing the three separate components, a discussion is relevant about the research approach to be followed when studying the waste-soil-water Nexus. Separate disciplinary approaches for each of the three elements cannot, as such, provide adequate results.

3 Researching the Nexus

Each of the three components of this particular Nexus has a rich research history by itself. The soil science discipline consists of a number of subdisciplines, such as soil physics, chemistry, biology, and pedology, that have a rather distinct character with their own subdivisions in scientific organizations and their own symposia and scientific journals. To some soil scientists, interdisciplinarity means that soil scientists in the various subdisciplines work together, which is, of course, rather different from the real interdisciplinary approach where soil scientists work with agronomists, hydrologists, ecologists, etc. Still, more interaction among soil subdisciplines is increasingly visible, and hydropedology is just one example (e.g., Lin et al. 2006).

Hydrology also has several subdisciplines. Most of the work focuses on the landscape or watershed level with a dominant role for simulation models. This is important for soils because fluxes of water, solutes, and energy are not restricted to the upper 2 m of the landscape soils but also follow deeper layers. This is reflected by considering the "critical zone," extending from the surface to bedrock, including the groundwater. Water movement in soils occurs dominantly in the unsaturated zone and is then seen as part of soil physics.

Waste research is quite diverse, covering the entire chain from waste generation to disposal. In the context of the Nexus, the volume of waste and its composition is the most important, and chemical analyses play a dominant part in its characterization.

When studying the Nexus, each of the three elements should ideally be characterized at a comparable degree of detail. Highly detailed analyses of waste material may not be needed when soil and water information of an area, where the waste will be deposited, is sketchy. Also, highly detailed soil information represents overkill when hydrological data is limited, and the same is true when hydrological information is quite detailed while soil information is lacking. To handle this problem, Bouma (1997, 2015) has proposed a step-by-step approach where in a first step the problem is analyzed by applying existing tacit knowledge for each of the three elements and, in the context of this position paper, the Nexus. Here, stakeholders have to be involved right from the start. Most likely, tacit knowledge is insufficient to arrive at a satisfactory analysis, resulting in an effective management scheme. The next step consists of adding information by involving expert knowledge based on existing information, making sure that the balance of information between the three elements is maintained. If this step still does not provide an adequate level for defining proper management, new research may be initiated, filling knowledge gaps identified. Each step results from interaction with the stakeholders. This way, three objectives are served: (1) the detail and level of knowledge of the three elements of the Nexus are in balance, (2) new research is defined on the basis of a defined need rather than being driven by the abstract curiosity of researchers, and (3) stakeholders are "owners" of the ultimate analysis as they have constantly been involved with the discussions. This is to be preferred over the more traditional procedure where researchers propose projects, often requiring substantial new research as a prerequisite to receive research grants, while application of existing expertise could well have been adequate (e.g., Bouma et al. 2015). With these considerations in mind, the three elements of the Nexus will now be discussed.

4 Waste

Attention in the waste-soil-water Nexus is on solid or liquid waste that enters the soil, thus becoming part of the physicochemical and biological processes in the soil, and whatever remains of the original compounds percolates downward or sideways, depending on the landscape position of the soil. Of the often-quoted 3Rs for waste management, *reduce*, *reuse*, *and recycle*, the first two have an impact on the composition and quality of the waste products entering the soil. Recycling not only takes place at the source of the waste but also includes soil processes transforming waste products in the soil, when they improve soil functions. Important processes of waste management, such as building landfills, applying incineration, aerobic activated sludge treatment, anaerobic septic tank treatment, or ecological treatment in reedbed systems in constructed wetlands, are not considered here as we focus on waste, liquid or solid, as it is presented to the natural soil-water system. Obviously, such different treatments result in different types of waste.

Waste products are highly heterogeneous in terms of composition because of their origin: water, organic particles, soluble organic matter, pathogens, soluble inorganic and organic compounds, salts, toxins (e.g., pesticides, poisons), and pharmaceuticals (e.g., hormones). A large number of methods are available to determine the composition of waste products (e.g., APHA 2012; US-EPA 2012). Important key attributes are the biochemical oxygen demand (BOD) which characterizes the biodegradable pollutants and the chemical oxygen demand (COD) that measures the oxidizable pollutants. Numerous methods are available to measure contents of heavy metals (Cu, Cd, Pb, etc.) or organic compounds. Bacteriological characterizations often include *fecal coliforms* as indicators of fecal waste.

An important link between solid waste and soil is compost. Large facilities are operational by now. The Edmonton Composting Facility is the site of the city of Edmonton's co-composting system for processing organic waste. Co-composting involves mixing household wastes with biosolids (sewage sludge) and using microorganisms to break them down into simple compost. Together with the city's three recycling programs, Edmonton was able to divert 60 % of household waste from landfills in 2009. By 2013, the city anticipated that it would divert more than 90 % of the city's household waste from the landfills. The co-composter is the largest in North America by volume and capacity. It can process 200,000 tons (220,000 t) of residential waste and 25,000 tons (dry) of biosolids each year. It is also the largest stainless steel building in North America. It occupies an area the size of eight Canadian football fields: 38,690 square meters. The Qatar Domestic Solid Waste Management Center is the largest in the Middle East. The Lahore Composting Facility has been partly funded by the Danish Carbon Fund (DCF) as well as by the Carbon Finance Fund of the World Bank (https://wbcarbonfinance.org). Overall, it is clear that composting part of urban solid waste is a technically feasible procedure that is being introduced on a wide scale. What happens next, when compost is added to the soil, is to be discussed next.

The European Union has been effective in providing a number of waste regulations, such as the "Waste Framework Directive 2008/98/EC," the "Hazardous Waste Directive 91/689/EEC," and, especially, the "EU Sewage Sludge Directive 86/278/EEC" which is the only regulation worldwide which defines threshold values for seven heavy metals in soils amended with sewage sludge. These directives can be accessed at EU websites.

5 Soil

5.1 Introduction

Many different types of soil are distinguished by soil classification systems in different countries. Two international systems are widely used in pedology, the study of soils as they occur in nature: soil taxonomy from the US Department of Agriculture (Soil Survey Staff 1999) and the international soil reference base (FAO 2006). Soil names are based on stable soil characteristics, such as texture, mineralogy, and %C, while also easily observable colors play an important role. Soil classifications are used as legends of soil maps that are widely available. Mapping units are named for a given soil type that is documented by physical and chemical data, usually available in accessible databases. However, the internal variation within mapping units is not known, and internal homogeneity is usually assumed to be 60 %, meaning that the soil type occurs in at least 60 % of the area of the particular mapping unit. Emphasis in soil classification is on soil genesis, and there is therefore only a relatively weak link with functionality which is central for the waste-soil-water Nexus. Soil structure (the physical constitution of a soil material) is not part of soil classification but is very important for soil functioning as it determines flow patterns of water and the associated filtration and purification processes, as well as rooting patterns of plants (e.g., Bouma 1989, 1991, and Sect. 5.4).

Traditional soil surveys define suitabilities or limitations for a variety of land uses, but they are defined in relative terms as *slight*, *moderate*, *or severe.* This is not adequate to answer modern land-use questions (e.g., Bouma et al. 2012, 2015) but can be seen as the first step in the step-by-step research approach mentioned above. Not being satisfied with the qualitative nature of soil maps, much emphasis has been paid during the last decade on digital soil mapping where physical and chemical characteristics are systematically assembled for 100m × 100m grids (Arrouays et al. 2014). Original point observations are obtained from databases in areas where soil maps are available or new observations are obtained elsewhere. Point data is interpolated with geostatistical techniques to obtain expressions for areas of land, also indicating internal variability that is not defined in classical soil maps.

Why these details in this Nexus paper? Any interested non-soil scientist may become confused when consulting soil maps or papers covering digital soil mapping, and the brief analysis provided here may clarify the different approaches being followed at this time. For this Nexus paper, three soil processes are important: (1) incorporation of organic waste products, (2) infiltration and flow patterns of wastewater, and (3) purification by percolating wastewater. These processes need to be placed in a broader context of soil functioning that will first be discussed.

5.2 The Seven Soil Functions

Part of a proposed soil protection strategy by the European Union in 2006 (CEC 2006) was the definition of seven soil functions:

1. Biomass production, including agriculture and forestry
2. Storing, filtering and transforming nutrients, substances and water
3. Biodiversity, such as habitats, species and genes
4. Physical and cultural environment for humans and human activities
5. Source of raw materials
6. Acting as carbon pool
7. Archive of geological and archaeological heritage

These functions are directly related to ecosystem services and the UN Sustainable Development Goals (Bouma 2014), but in the context of this paper, the relevant question is how the addition of either wastewater or solid waste can improve the particular soil functions of a given soil that occurs in a given landscape and is subject to a given climate as part of the hydrological and energy cycle. Future questions focus on what the effects of climate change may be. At first sight, one would expect that functions 1, 2, and 6 could be particularly affected, but this needs further elaboration.

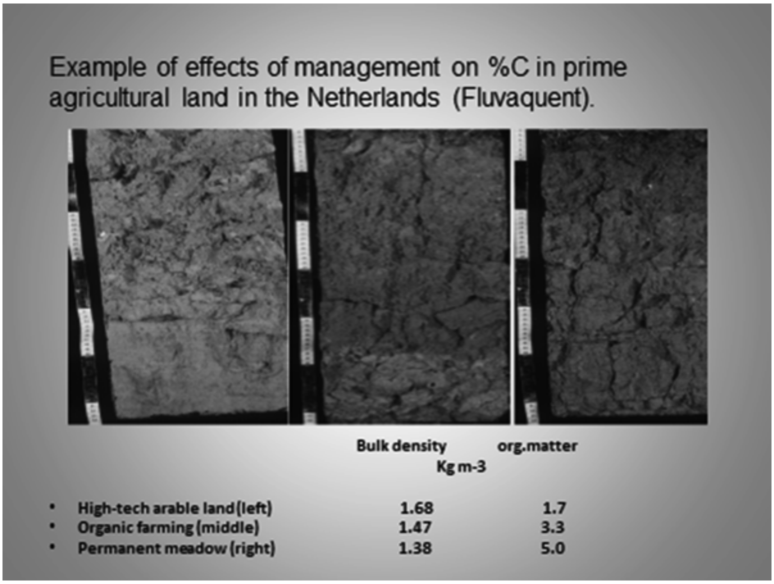
In addition to being directly relevant for ecosystem services and UN Sustainable Development Goals, the soil functions can also be applied to define the elusive term of soil quality. In contrast to water, where quality-related threshold levels have been defined (think, e.g., of the 50 mg/l nitrate concentration as a threshold for drinking water quality), such values do not exist for soils. Clearly a single quality measure cannot be defined, because the quality, defined here in terms of the “ability to perform," may be high for function 1 but low for functions 4 and 7. Also, function 1 may adversely affect function 3, etc. It would therefore be pragmatic to define soil quality for each of the functions which could be valuable when developing regional land-use plans implying a mix of functions that are acceptable to local stakeholders and policymakers. Focusing certain functions on areas where such functions have a high value would represent a logical approach. Bouma et al. (1998) and Bouma (2002) proposed a quality indicator for the important function 1: biomass production. Potential productions can be estimated based on radiation and temperature levels, assuming that water and nutrients are abundantly available and that pests and diseases don't occur. More realistic is the so-called water-limited yield, which is based on available water at a given location which, in turn, is based on precipitation and the water-holding capacity of the soil, again, assuming optimal fertilization and no pests and diseases. Generally speaking, water availability is more difficult to manage than fertilization and pest control, and this explains the distinction of the water-limited yield. The ratio potential production/water-limited yield is considered a quality measure of any given soil. When multiplied by 100, a value between 0 and 100 is obtained. Examples are presented by Bouma et al. (1998) and Bouma (2002). Of the other functions, function 3 can be important as well because adding organic matter to soil may increase biodiversity, while adding waste is likely to affect the living environment as well as indicated in function 4. However, in the context of the NEXUS emphgasis on functions 1,2 and 6 may be most relevant.

5.3 *Soil Organic Matter*

Soil organic matter plays a key role in the soil functions. Higher organic matter contents are associated with a higher water-holding capacity and a better, more friable, soil structure, both favorable for biomass production (function 1). But also filtering (function 2) is improved because of its adsorptive capacity. Higher organic matter contents are also associated with a higher biological activity, improving function 3, and, obviously, function 6 benefits from an increase in organic matter content. Lal (2014) has presented an excellent overview of organic matter in soil.

Solid waste and wastewater contain organic matter that, when added to soil, can increase the organic matter content of the soil when it stimulates biological activity that is needed to incorporate the added organics into organo-mineral complexes. This process can be hampered by heavy metals or certain organic molecules, so the quality of the waste has to be known before it is applied to the soil. Interestingly, Lal (2014) does not discuss liquid or solid waste application to soils when analyzing management measures that can result in C-sequestration. He only considers recycling agricultural waste. This can be due to the expected adverse effects of heavy metals and organics, as mentioned above.

Figure 7.1 shows the effects of organic manuring on a prime agricultural clayey soil in the Netherlands. Conventional high-tech tillage and management practices resulted in a high bulk density of 1.68 g/cm3 and a very low %C of 1.7 %. Organic farming, including addition of organic manure and compost, resulted in a lower bulk



Example of effects of management on %C in prime agricultural land in the Netherlands (Fluvaquent).

	Bulk density Kg m-3	org.matter
• High-tech arable land (left)	1.68	1.7
• Organic farming (middle)	1.47	3.3
• Permanent meadow (right)	1.38	5.0

Fig. 7.1 Three phenoforms of the genoform Fluvaquent, expressing the effects of management on bulk densities and %C, considering current and past land use (From Droogers and Bouma 1997)

density of 1.47 g/cm3 and a %C of 3.3 %. This soil had a more friable structure. Values were even better under permanent meadow with 1.38 g/cm3 and 5.0 %C, respectively. Note that the soil type (the genoform) was the same, even though soil behavior was quite different, thus defining different phenoforms (Droogers and Bouma 1997).

How to relate effects of adding waste to the organic matter content of soils? There are many simulation models for carbon interactions in soil, but processes are quite complicated, and we have suggested the alternative to identify parcels in the field where – according to the soil map – a given soil type occurs and study its properties as a function of past management that can be recorded by interviewing farmers and land users. Changes in %C take many years to materialize. Short-term experiments are therefore not feasible. The results of many real-life "experiments" are to be observed in the field, and our research showed that regression equations could be derived relating %C to past land use (Pulleman et al. 2000, Sonneveld et al. 2002).

As mentioned above in the section on waste, compost from urban waste to be applied to the soil is now successfully produced in many countries. The Food and Agriculture Organization (FAO) of the United Nations produced an early bulletin in 1987 covering soil management of compost in tropical and subtropical environments. They focus primarily on the composition and handling of compost and pay little attention to soils and soil processes. More recently, different states in the USA have published best management practices for compost on agricultural soils. The state of Washington has produced an excellent fact sheet (http://www.ecy.wa.gov/programs/swfa/organics/soil) that defines five important functions of compost: (1) increase the infiltration rate of the soil and water retention of topsoil; (2) reduce surface run-off because of higher infiltration rates; (3) trap sediments, heavy metals, excess nutrients, and biodegradation of chemical contaminants; (4) promote the possibility to create a protective vegetative cover; and (5) support beneficial soil life, fighting pests and diseases and supplying plant nutrients. This would possibly result in lower use of chemical fertilizers and biocides. The fact sheet provides detailed management recommendations. No supporting data for these five claims is, however, provided by referring to literature, nor is there reference to the possibly different requirements of different soil types. Also, the University of Florida provides detailed management recommendations, again without supporting data or emphasis on soils (http://ipm.ifas.ufl.edu/resources/success_stories/T&P/). A study in Senegal does provide more details on soil processes (Mc Clontock and Mahktar Diop 2005). The "Joor" (Dior) soils of Senegal's Peanut Basin are inherently low in organic matter, limiting yields of millet and other crops and threatening the food security of smallholders. The "Joor" soils occupy 70 % of the area and are sandy (Ustipsamments according to Soil Survey Staff 1998), and 30 % of the area in the lower parts has soils ("Deg" soils) with a more clayey texture (Psammentic Haplustalf). Focus groups and interviews were conducted in eight villages to characterize the site-specific fertility management by farmers in the Peanut Basin. Results of the qualitative survey revealed that farmers base management decisions on a series of fertility indicators that include type, color, and texture of soil, presence of vegetation, and productivity in previous years.

In an effort to equalize fertility across the field, farmers amend areas they classify as less fertile with decomposed manure and household waste from the family sentaare (traditional pile) or with compost from managed piles. On-site measurements of soil in areas of fields [connect with next line!]

amended with compost or sentaare material revealed significant increases in peanut and millet growth over unamended areas but little difference between the effects of compost and manure. Similarly, chemical analysis revealed increased effective cation exchange capacity (ECEC) and nutrient concentrations (K, Mg, and Al) in soils amended with compost or manure. Similarities in the chemical characteristics of compost and sentaare material suggest that development workers could emphasize improved pile management rather than promoting more labor-intensive composting. This particular study includes a high-standard soil analysis and puts the application of compost and animal waste into a broader socioeconomic context, which is important and not only for developing countries. By linking results to particular soil types, as defined by Soil Survey Staff 1999, results can, in principle, be extrapolated to other areas with similar soils (and climatic conditions).

5.4 *Soil Permeability*

The capacity of soils to accept liquid and conduct it downward is a key element of the waste-soil-water Nexus. Unfortunately, there is a gap between soil physical theory of water movement in soils and development of measurement methods on the one hand and their application in the field in the context of practical projects, on the other. The so-called soil percolation test is still being used to define critical infiltration rates for on-site liquid waste disposal (e.g., Bouma 1979). It consists of digging a hole, pouring in water, and observing the rate by which the water moves downward. This yields physically undefined values that can range widely when measured at different moments in the same soil. Physical flow theory is needed to better characterize wastewater movement in soils, particularly since flow occurs in unsaturated soil. Steady flow of liquid through saturated and unsaturated soil can be described by the well-known Darcy flow equation:

$$q = K \bullet \left(\mathrm{d}H \,/\, \mathrm{d}z\right) \tag{7.1}$$

where q = flux (cm/day); $\mathrm{d}H/\mathrm{d}z$ = gradient of the hydraulic head (cm/cm), the latter composed of the pressure potential h, due to capillary forces (cm), and the gravitational potential Z, due to gravity (cm) $(H = h + z)$; and K = hydraulic conductivity (cm/day), which is equal to the

flux when the hydraulic gradient is one. Saturated soil, in which all pores are filled with water, has the highest K value ($Ksat$). A high $Ksat$ value as such does, of course, not imply that water moves rapidly through the soil, because this will depend on the hydraulic gradient. When the gradient is zero, nothing will move. Moisture contents below saturation are associated with lower K values because the available water is contained in the smaller pores due to the relatively high capillary forces they can exercise as compared with the large pores and because smaller pores can conduct much less water than larger ones at a given hydraulic gradient. Soils may be unsaturated as a result of either barriers at the infiltrative surface or an application rate which is lower than $Ksat$. The decrease of K upon decreasing moisture content is characteristic for each soil material, because it is a function of the pore size distribution. K can be presented as a function of the pressure potential (h) or of the moisture content. Emphasis on this aspect of soil physics is necessary because real flow rates of effluent into and through the soil must be known to allow rational sizing of systems. Unfortunately, a simple flow meter for direct measurement of flow rates in unsaturated soil does not exist. The *indirect* procedure to be followed involves the in situ measurement of pressure potentials with tensiometers (which yields $dHldx$). By reading the appropriate K values from a K-h curve, a flux q can be calculated according to Eq. 7.1.

This approach has been followed to characterize the effects of clogged layers and crusts on infiltration in operating waste disposal systems and to calculate their resistance (Bouma 1975) as follows:

$$q = Kb \cdot \left[\left(Ho + M + Zb\right) / Zb\right] = \left(l \,/\, Rb\right) \cdot \left(Ho + M + Zb\right) \tag{7.2}$$

where Kb = hydraulic conductivity of the barrier (cm/day), Ho = the positive hydraulic head on top of the barrier (cm), M = pressure potential in soil below the barrier (cm), Zb = thickness barrier (cm), and $Rb = ZblKb$ = hydraulic resistance (days) of the barrier, which can be calculated if the other terms are known. Knowing Rb,

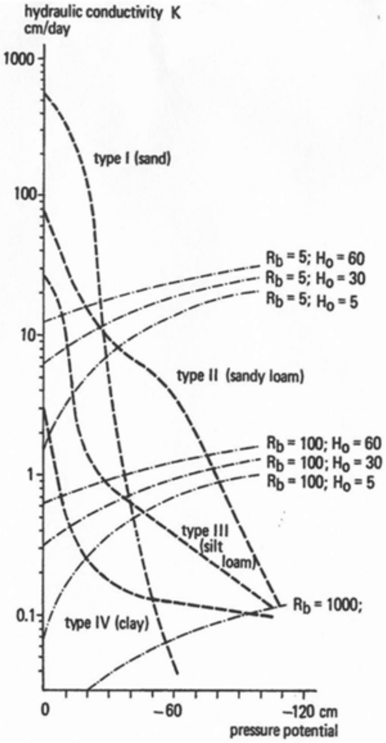


Fig. 7.2 Hydraulic conductivity curves of five parent materials with different textures. The dotted curves indicate the effects of crusts on infiltration rates of liquid as a function of crust resistance and the ponding level in the seepage trench as explained in text (From Bouma 1975)

a functional relationship between M and q (the latter is usually equal to K during steady flow) can be found for given values of Ho and Zb. This allows a *prediction* of the hydraulic effect of barriers on different soils (Bouma 1975).

Figure 7.2 shows K curves for different textures. While the conductivity for sand, with many relatively large pores, is high at saturation, it decreases rapidly when the soil becomes less saturated (at decreasing pressure potentials). This implies that at a suction of, for example, −60 cm, the conductivity of a clay soil is higher than that of a sandy soil. This is an important fact for waste disposal in soil, because at lower flow rates larger pores are filled with air and this enhances the purification potential because it allows oxidation processes. Figure 7.2 also indicates the calculated effects of different types of crusts (each with a given resistance Rb) and ponding depth in the seepage trench on infiltration rates. This allows exploratory calculations when designing seepage fields.

After excavating on-site waste disposal systems in sands, unsaturated soil was observed next to the disposal field. This was due to a crust, formed by bacteria on the face of the seepage bed (Bouma 1979). The measured pressure head was −20 cm, corresponding with approximately a K value of 5 cm/day in sand (Fig. 7.2). After finding comparable results in other sandy soils, this flow rate was used to size seepage fields, given a certain expected flow of wastewater. Such clear relations were not found for other soils but could be used in "mound systems" (to be discussed later) in which 60 cm of sand was deposited on top of a slowly permeable soil and effluent was discharged on the sand (Bouma 1979).

Hydraulic conductivity values can be measured, but this is time consuming, and increasingly soil data are used to calculate K values by correlating with texture, %C, and bulk density, using so-called pedotransfer functions (PTFs) (Wösten et al. 1999; Bouma 1989). This is attractive but also risky in that the relation with the soil in the field gets lost when PTFs are automatically included in simulation protocols. Then, PTFs may be applied to sites where they can't be applied because the PTFs were derived from data derived from different soils. Another problem is the underlying assumption of physical flow theory that soils are isotropic and homogeneous. Of course, they are not. Occurrence of large soil pores (macropores such as worm channels or cracks in clay soils) may rapidly conduct water from the soil surface to great depth, bypassing the matric of the soil (this process is called "bypass flow") (Booltink and Bouma 2002). Bouma (1989) showed that water sprinkled on a silt loam soil with vertical worm channels. An example is shown in Fig. 7.3 (from Bouma 1989), where water was sprinkled on a silt loam soil with worm channels. Water moved to great depth almost instantly, and the same would happen with wastewater, presenting a clear risk for groundwater pollution. Disrupting the continuity of the macropores, for example, by shallow surface tillage, may be effective in avoiding bypass flow.

Another problem is the fact that flow patterns are not necessarily vertical but may also be lateral, certainly in sloping land and when subsurface soil horizons are slowly permeable. This should be taken into account when considering the hydraulic conductivity of a soil that is to be used for waste disposal. Liquid waste deposited upslope may unexpectedly surface downslope after too short a travel time. Soil survey information provides soil data, allowing distinction of these hillside effects.

5.5 *Soil Purification*

Soil is highly effective in storing, filtering, and transforming waste components as they move down through the soil. Dissolved inorganic and organic compounds can be adsorbed, but soils vary widely in terms of their adsorptive capacity as a function of pH, content and type of organic matter, clay minerals, and various oxides. Preferential flow patterns along macropores in well-structured soils may have the effect that waste components bypass the adsorptive soil complex and reach the groundwater (see Fig. 7.3). Model calculations, assuming soils to be isotropic and homogeneous, will produce misleading results under such conditions. Soils can also be quite effective in filtering pathogenic viruses and bacteria. However, the common question "how much soil is needed to achieve adequate filtration" cannot be answered as it depends on the flow rate and the associated travel time as the liquid moves through the soil. An example for sand is shown in Fig. 7.3 (Bouma 1979). A solution with a high content of pathogenic viruses was applied at 5 cm/day and, in other columns with the same sand, at 50 cm/day. The low flow rate resulted in a

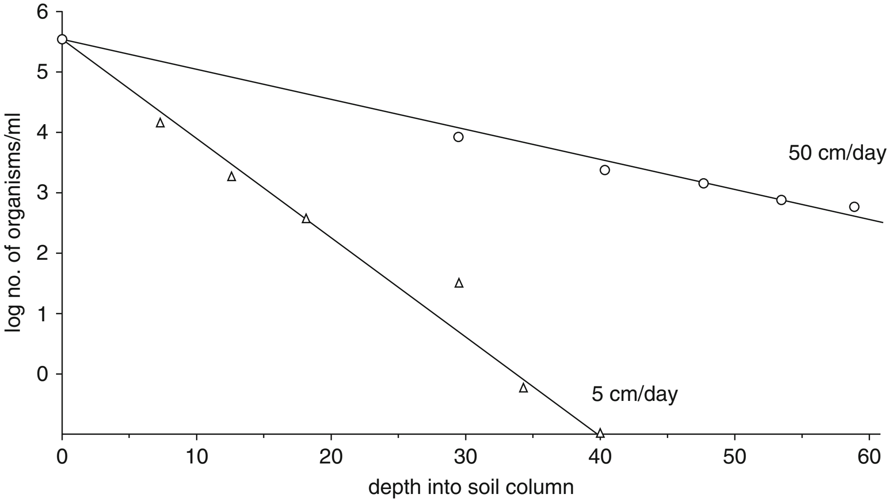


Fig. 7.3 Movement of septic tank effluent spiked with pathogenic viruses in a 60 cm-long soil column filled with sand. At a flow rate of 5 cm/day, viruses were never observed below a depth of 40 cm. Filtration was effective due to the relatively low flow rate (and a long travel time) in unsaturated sand in which larger pores were filled with air. At 50 cm/day, filtration was inadequate as water moved quickly through the larger pores. Each soil has a characteristic relation between flow rates and travel times which are directly linked with filtration due to contact with the soil material and oxidation

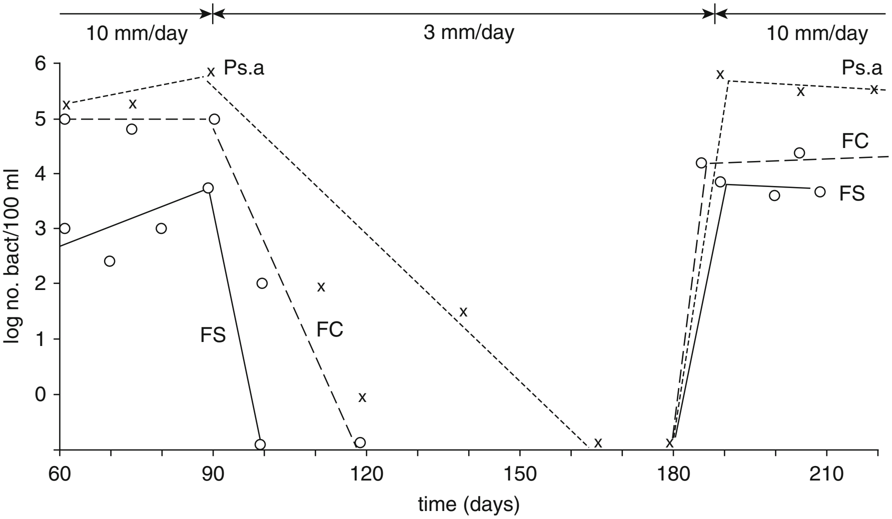


Fig. 7.4 Movement of septic tank effluent spiked with three bacteria (*Pseudomonas aeruginosa*, *fecal Streptococcus*, *and fecal coliform)* through a 60 cm-long column filled with an undisturbed silt loam soil. At a flow rate of 10 cm/day, the liquid moves relatively rapidly along the faces of structural elements (peds), and many bacteria leave the column. At 0.3 cm/day, flow occurs mainly through the peds, resulting in longer travel times and complete purification

relatively long retention time because the soil was not saturated. Moreover, large pores were filled with air, creating an oxidative environment. Viruses never moved out of the 60 cm-long column. They did in a high quantity at the higher flow rate, with a shorter retention time. Figure 7.4 shows what happened in a well-structured silt loam soil. Here, at flow rates higher than 3 mm/day, liquid moved along the larger pores, surrounding the structural elements, while at lower fluxes they moved through the elements, resulting in longer travel times and perfect filtration. No bacteria left the column, while they did at the higher flow rates. The system was continued for 18 months and the process could be repeated several times.

In conclusion, when considering soil function 2, it is important to consider retention times in unsaturated soil, which may have a two-dimensional character in sloping soils. Every soil has a characteristic set of retention times as a function of the flow regime and, therefore, a characteristic range of filtration potential. Unfortunately, this aspect, connecting hydropedology to health aspects, has not received adequate attention in soil research on liquid waste disposal ignoring unsaturated conditions in the field.

6 Water

Water in soil, emphasizing unsaturated conditions, has been broadly discussed in Sects. 5.4 and 5.5, illustrating, as such, the relevance of hydropedology. But hydrology has also an important function to characterize the regional dynamics of water, for example, in watersheds. This way the effects of waste disposal at a given location on conditions in a wider region can be determined either by measurements or by simulation modeling. Bouma et al. (2011a) and Droogers and Bouma (2014) have, however, pointed out that quite a few hydrological models currently being used do not adequately reflect soil conditions as many models don't incorporate soil data.

Water-related problems are diverse and location specific. The ideal condition of having the appropriate amount of good-quality water at the desired place and time is most often not satisfied. Because so many different problems may have to be solved, the broad concept of integrated water resources management (IWRM) was introduced and has been advocated over the last decade (e.g., Vannevel 2011). More recently, IWRM has been expanded by integrating all water resources, not only water in streams and reservoirs as was the original base for IWRM. This extended approach to IWRM is now being advocated and is often referred to as including "blue" and "green" water, making the distinction between free water in streams and reservoirs and water available in unsaturated soils to be used by the vegetation or crop, respectively (Falkenmark and Rockström 2010). This expansion was necessary because many policymakers still limit water issues primarily to drinking, sanitation, industrial, and irrigation use.

Relevant information, based on reliable data, is essential to assess not only the current condition of water resources in a given basin but also past trends and future possibilities. To explore options for the future, tools are required that can explore the impact of future trends and possible ways of sustainable adaptation. Climate change implies that expert knowledge based on past conditions cannot adequately address such future trends. Simulation models that can explore future conditions are therefore appropriate and indispensable tools for such analyses. A huge number of hydrological models exist, and applications are growing rapidly. The number of pages on the Internet including “hydrological model” is over 5.8 million, using Google in January 2014. Using the same search engine with “water resources model” returns 150 million pages. The number of existing hydrological simulation models is probably in the tens of thousands. Even if we exclude the one-off models developed for a specific study and count only the more generic models, it must exceed a thousand. Some existing model overviews cover numerous models. For example, REM (2014) covers 681 models. No standard model or models appear to be emerging for catchment modeling, which is in contrast to groundwater modeling, where ModFlow is the de facto standard. Two hypotheses for this lack of standard in catchment models can be given. First, model development is still in its initial phase, despite some 25 years of history, and therefore it is easy to start developing one’s own model that can compete with similar existing ones within a reasonable amount of time and effort. Indeed, a serious hydrologist is considered to have his or her own model or is supposed to have at least developed one during his or her PhD studies. Second, hydrological processes are so complex and diverse that each case requires its specific model or set of models.

7 The “Nexus” as a Communication Tool to Societal Partners

The Nexus approach ideally will link waste, soil, and water in a logical story line and in doing so avoids exclusive emphasis on either one of the three elements, which is common in disciplinary research. But a logical story line is not enough! The development and introduction of information and communication technologies (ICTs) have, certainly in the last decade, fundamentally changed information flows within society. Unlimited accessibility of unfiltered data and information at the touch of a button has provided the illusion to many that they can know all there is to know. In their view, the scientific community just delivers “yet another opinion” (e.g., Bouma 2015). Authority is not anymore derived from a given position in society but has to be earned, and one-liners are often more convincing in the impatient information arena than scientific arguments that realistically emphasize uncertainties. Some even argue that the science community has to earn again its “societal license to research.” Be that as it may, the science community would be well advised to make a critical analysis of their approaches and rituals in view of these changing societal conditions. This certainly is relevant for the Nexus discussion. Rather than be reactive, a proactive approach is bound to be more effective. This is the more relevant since the content of scientific meetings and journals and administrative and evaluation procedures of the profession don’t appear to have changed much during the last decade.

Starting in the 1980s, multi-, inter-, and transdisciplinary research approaches have been proposed, realizing that when studying sustainable development, different scientific disciplines have to be involved as well as various stakeholders and members of the policy arena. Here, multi- and interdisciplinarities describe cooperation between different disciplines, in the first case working rather independently and in the second case with much interaction. Transdisciplinary approaches directly involve stakeholders (e.g., Bunders et al. 2010). Thomson Klein et al. (2001) proposed the following definition of transdisciplinarity: "Transdisciplinarity is a new form of learning and problem solving involving cooperation between different parts of society and science in order to meet complex challenges of society. Transdisciplinarity research starts from tangible, real-world problems. Solutions are devised in collaboration with multiple stakeholders."

Many papers and books have appeared covering the changing relationships between science and society. The influential book by Gibbons et al. (1994) distinguished traditional monodisciplinary mode-1 science versus transdisciplinary mode-2 science in which scientists of different disciplines work together with various stakeholders and policymakers. Mode 1 occurs in an academic context, while mode 2 operates in a context of application and is thus more problem oriented. Mode 1 is characterized by autonomy, based on the independence of science, while mode 2 is subject to social accountability. Also, quality control is different. Mode-1 research has traditional quality control in terms of the number of publications as expressed in citations and h-factors, while mode-2 research is judged by as yet to be agreed upon procedures also considering societal effectivity. The mode-2 approach certainly reflects societal concerns about the role of science, but many scientists are rightly concerned that an unqualified shift to mode 2 could involve loss of independence and scientific quality, which are both essential ingredients of science. Also, focusing on mode 1 is at this time more attractive for soil researchers from a career perspective: writing disciplinary papers produces more credits in a given amount of time than time-consuming mode-2 studies that are also more difficult to publish. Evaluation systems are currently rather strongly focused on the number of peer-reviewed publications even though changes are proposed (e.g., VSNU-NWO-KNAW 2014; Bouma 2015).

Several transdisciplinary methodologies have been developed. For example, the Swiss Transdisciplinary Case Study (TCS) approach (Scholz et al. 2006) distinguishes six steps in research. The German Institute for Social-Ecological Research (ISOE) (Jahn and Keil 2006) defines ten principles. The interactive learning and action (ILA) approach (Bunders et al. 2010) distinguishes five phases in research, and the B-sik TransForum program in the Netherlands on sustainable agriculture (van Latesteijn and Andeweg 2011; Bouma et al. 2011b) defines a "connected value development" principle (linking essential values of various stakeholder groups), distinguishing "proposition" (defining all values), "creation" (defining all options and develop one that is acceptable to all), and "capture" (realizing the one option in practice). Sayer et al. (2013) presented ten principles for a landscape approach to reconcile competing land uses, and several of these principles reflect what has been reported in the literature cited above. They also present a number of case studies that demonstrate what are in effect successful transdisciplinary research projects, even though the term as such is not used. This illustrates the impression that many successful transdisciplinary studies have been made but not reported in literature where more attention has been paid to disciplinary papers covering certain aspects of any given study. This certainly applies to disciplinary waste, hydrology, and soil studies as well.

However, as is, standardized and widely accepted procedures for transdisciplinarity, including its evaluation, are not available yet. This is in contrast to basic research where evaluation protocols emphasize publications in international peer-reviewed journals and citation indexes. Lack of transdisciplinary criteria implies in practice that criteria for basic studies are also applied to transdisciplinary studies and this creates problems that discourage these types of time-consuming studies.

Wenger et al. (2002) recognized the need for cooperation between researchers and stakeholders by defining communities of practice (CoP) implicitly and somewhat arrogantly assuming that the scientific community would be able to effectuate this type of cooperation. Bouma et al. (2008) challenged this assumption and proposed to first establish a community of scientific practice (CSP) before seriously engaging in stakeholder involvement. A CSP would define different career tracks for scientists, each one with an attractive professional perspective: Track 1: basic researchers, to be evaluated by well-known publication criteria. Their role is crucial for the future of soil science, and they should not be distracted by activities that inhibit their scientific work. Track 2: researchers able to link with adjacent disciplines for soil science such as agronomy, hydrology, climatology, and geology. They would be evaluated by their ability to realize effective interdisciplinary studies. Track 3: knowledge brokers with social intelligence, able to inject the right type of knowledge at the right time and place to the right person in the right way. Track 4: a versatile technical staff.

When considering the waste-water-soil Nexus, it would be wise to not only focus on interdisciplinary aspects and the level at which each component is represented, which is already quite valuable, but to also extend the analysis to transdisciplinarity which becomes increasingly important in the twenty-first century. The Nexus will only come alive when it is embraced and internalized by stakeholders and policymakers, and this requires a special effort.

8 Case Studies

A number of case studies and conferences will be briefly reviewed to illustrate aspects that have been mentioned in this paper. The selection from an overwhelming quantity of papers, reports, and proceedings in literature has to be arbitrary and will focus on the degree in which true links were established between waste, soil, and water as expressions for an effective Nexus.

8.1 Scenarios for Waste Disposal: An Example for Kampala City, Uganda

Emphasis in this position paper is on the relations between waste, water, and soil and centers therefore on soil processes interacting with solid waste and wastewater. But it is important to also see the bigger picture where, for example, cities have to choose between different options of waste disposal which don't necessarily imply that on-site disposal on soil plays a major role. This example is therefore included to illustrate this broader scope of the waste problem. Oyoo et al. (2014) report that poor waste flow management in East African cities has become an environmental and public health concern to the city authorities and the general public. The environmental impacts of waste recycling in Kampala City were developed for four waste management scenarios, namely: (1) scenario 1 representing the current status quo; (2) scenario 2 maximizing landfill; (3) scenario 3 combining composting, resource recovery, landfill, and sewerage; and (4) scenario 4 integrating anaerobic digestion, resource recovery, landfill, and sewerage. These scenarios were quantitatively assessed for environmental impacts of global warming, acidification, nutrient enrichment, photochemical ozone formation, water pollution, and resource conservation. Sensitivity analyses were performed on the robustness for the ranking of the scenarios. Scenario 4 performed best for all environmental impact categories. Sensitivity analysis showed this assessment result to be robust. Anaerobic digestion and composting yields productive manure for soils, but effects on soils are not further explored in this study that concludes that integrating waste recycling into the formal waste management system for Kampala would considerably reduce the environmental impacts of waste flows. Also, considering the similarities in municipal solid waste compositions, sanitation systems, and settlement patterns among the large cities in East Africa, assimilating waste recycling into the formal waste management systems for these cities would result in minimal environmental impacts for their waste flows. The waste-water-soil Nexus is highly relevant in this context.

8.2 The International Istanbul 3W Congress

An international conference on solid waste, water, and wastewater was held in Istanbul in 2013 (www.Istanbul3Wcongress.org). Fifty-three papers were presented on solid waste, 45 on water, and 50 on wastewater. The solid waste papers focused on technical procedures. Kiris et al. (page 19 in abstract book) described compost production for domestic waste in Istanbul. Each day appr. 60000 t of solid waste are produced of which 700 t are suitable for compostation. Fermentation takes appr. 8 weeks and the compost is used for horti- and agriculture. No information on soils and on soil improvement is provided, nor was soil mentioned in the section on water. Dichl et al. (page 240 in abstract book) reported on the classic long-term wastewater reuse program in Braunschweig, Germany, by now a 60-year-old success story. Wastewater is biologically treated with an activated sludge process and has afterward a quality allowing discharge in surface water. 2700 ha of agricultural land is irrigated each year. This is essential for agricultural production because the precipitation deficit in the growing season averages 300 mm. In the growing season, digested sludge with N and P is added to the irrigation water to support plant growth. Each year 10 million m3 of wastewater is used with 100 t of P and 400 t of N, reducing the need for applying chemical fertilizers. Heavy metals are screened out at the factory source. Only processed crops like corn, rye, and wheat are irrigated. Irrigation is stopped well before harvest to avoid bacterial contamination. Aerosol drift is avoided by surrounding the fields with hedges. No details are provided on the effects on the soil nor is there consideration of the hydrological cycle where addition of purified wastewater is likely to be effectful. Both studies are rather straightforward as they identify agri- and horticultural needs as a means to deal with a solid and liquid waste problem. Other scenarios to possibly solve their problems are not discussed. Still, the cases present clear examples of the waste-soil-water Nexus.

8.3 Soil Disposal of Septic Tank Effluent

A fact sheet of the US Environmental Protection Agency (EPA) indicates that 20 % of US housing units have septic systems, discharging anaerobically treated liquid waste into subsoil seepage beds. In a 1997 landmark report to the US congress, EPA concluded: “adequately managed decentralized wastewater systems are a cost-effective and long-term option for meeting public health and water quality goals, particularly in less densely populated areas” (http://water.epa.gov/infrastructure/septic/). In the EPA annual report of 2013 on “decentralized wastewater programs,” the state of the art is discussed. Most attention is paid to describe problems encountered when operating septic systems, as a result of excessive garbage disposal, input of household cleaners and toxics, and excessive water use by using hot tubs or by undiscovered leaks in the system. Improper design and installation is mentioned but not specified, while it represents a major reason for system failure. The septic tank itself is simple and reliable but not all soils are suitable, and improper construction practices can lead to compaction of the future subsurface infiltration surface with the effect that the system will not work right from the start. To characterize the infiltration capacity of soils, the percolation test is still being used, which is undefined physically (see discussion in Sect. 5.4). The Small-Scale Waste Management Program in Wisconsin in the early 1970s (Bouma 1979) concluded that effective infiltration and purification of liquid waste require unsaturated flow that is high enough to not require a very large seepage area and low enough to allow purification by a sufficiently long travel time, as discussed above. Travel times are characteristically different for different soils, and different soils need therefore different disposal systems also considering water table levels, because there should at least be a soil-specific travel time of effluent through unsaturated soil before it joins the groundwater. Adequate representation of soil processes requires consideration of unsaturated flow which is as yet not considered in environmental regulations. Field measurements proved the existence of stable biological crusts in ponded seepage beds in sands (see Sect. 5.4) inducing a negative pressure head in the soil of −20 cm, corresponding with a flow rate of appr. 5 cm/day (as derived from the hydraulic conductivity curve). That 5 cm/day was next used to size seepage fields in natural sands, considering the expected flows of wastewater. The value was also used in “mound” systems for soils with high water tables or soils with slowly permeable subsurface soil horizons. After careful surface tillage of the original soil surface, 60 cm of sand was added on top of these soils and covered with a shallow layer of topsoil on which grass was grown (no trees because tree roots could disrupt the tiles in the distribution system, Fig. 7.5). Thousands of these mounds have been built in the Midwest of the USA and they seem to work well (e.g., Bouma et al. 1975). In all other more clayey soils, attention in the Small-Scale Waste Management Program was focused on avoiding formation of biological crusts on the surfaces of infiltration by intermittent application of waste, using pumps. Oxidation of the infiltrative surfaces between applications was intended to avoid formation of crusts. The few measurements made next to examples of crusts in ponded seepage fields in clayey soils showed negative pressure heads in surrounding soil with values of around −60 cm, which corresponded with flow rates that were too low to allow economic sizing of seepage fields. However, one major reason for system failure was compaction of the future infiltrative surface by machinery when constructing the field, resulting in very low infiltration rates. Then systems failed right from the start of operation. Of course, also in sands, intermittent application can be applied, but the observed 5 cm/day equilibrium value provides an extra safety valve.

The Soil Science Society of America organized a timely conference on on-site liquid waste disposal in 2014 (http://sci.soc.confex.com/scisoc/2014ww/webprogram/session13606.html). Keynotes covered the importance of climate change for the future performance of on-site systems and the possibilities to design web-based support systems, and R.L. Siegrist emphasized the need for engineering designs of modern soil treatment units, including the soil. Biological clogging of seepage beds was covered not in natural systems but in lysimeters that were also used to test intermittent drip applications. Amoozegar was the only author to present a study with tensiometers, piezometers, and time-domain reflectometry measuring dynamic hydraulic conditions around seepage systems, but the same author emphasized the use of Ksat in describing flow from seepage systems because, in his words, Kunsat would be too difficult to measure. This is not correct in our view. Methods to measure Kunsat are available and estimates can be made with pedotransfer functions (see Sect. 5.4). On-site liquid waste disposal is a matter of unsaturated flow, and only understanding of the unsaturated flow dynamics of a soil can answer basic questions on disposal versus purification, as discussed above. The paper with an EPA update was unfortunately not presented at the conference. Several papers emphasized the effectivity of pretreatment of the liquid waste by constructed wetlands, willow-based evapotranspiration systems, and the use of lagoons. This is attractive when enough land is available but no option in, for example, suburbs.

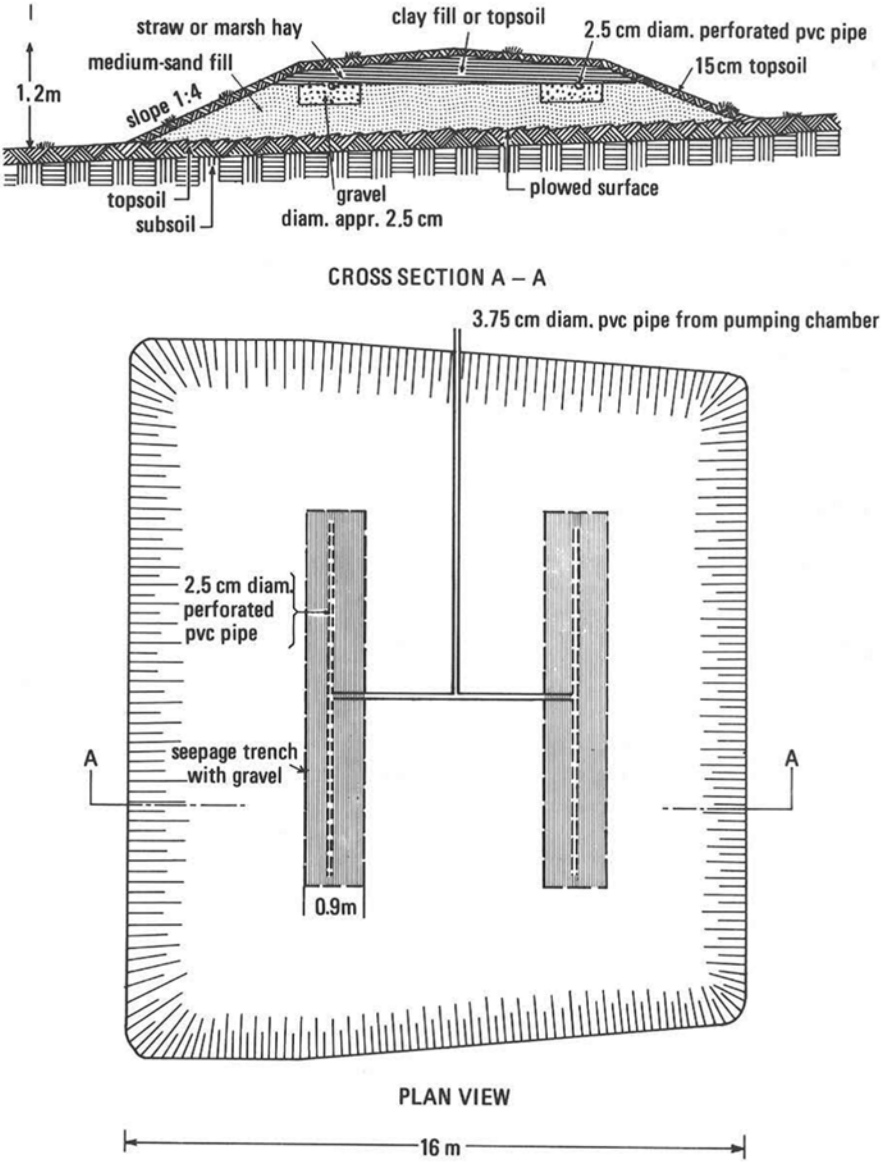


Fig. 7.5 Cross section and plan view of a mound system for on-site disposal and treatment of septic tank effluent in slowly permeable soils with seasonally high groundwater tables (Bouma 1979)

Barringer presented a life cycle analysis of the production process of all elements of a traditional septic system and compared this with using a tank made from recycled thermoplastics. Energy savings were an impressive 90 %! Overall, this conference served an important function in updating information on on-site liquid waste disposal, but lack of an analysis of unsaturated flow phenomena in soils was disappointing. Again, lack of alternatives in areas, where central sewage systems are unfeasible, results in a direct link between wastewater and soil, aimed at purifying the wastewater, representing a perfect waste-soil-water Nexus.

8.4 Soil Application of Olive Mill Wastewater (OMW)

At the soil-waste-water conference in Landau/Pfalz in 2013, attention was paid to the effects of applying OMW on soils (http://www.soil-water-waste.de). Different studies in Israel, Palestine, Jordan, and Spain showed that OMW is acidic, while its organic components are nondegradable due to toxic components (polyphenols). Treatment plants don't accept the waste because it disturbs regular treatment processes and the waste is therefore often discharged elsewhere which creates problems. Field and laboratory experiments showed that, indeed, acidification, increase of salts, and, particularly, hydrophobicity create problems. On the other hand, treated soils had more nutrients, particularly K and N, and %C increased as well. Experiments showed that phytotoxicity declined rapidly in soils, within a week, but this varied among soil types. Composting of the organic slurry paste (the olive mill pomace), followed by application to the soil, significantly improved soil fertility and soil structure. Advanced molecular analysis showed that after OMW application, the organic exchange complex not only had higher values but also adsorbed organics more effectively and even irreversibly. These studies clearly showed the importance for soil quality of applying OMW and represented, again, a direct example of a waste-soil-water Nexus approach.

8.5 Activities of IWMI

The International Water Management Institute (IWMI) (www.IWMI.org) published a flyer in 2014: "Making waves in the field of informal wastewater use." They point out that they were the first to draw attention to the fact that the 1989 guidelines of the World Health Organization (WHO), "guidelines for the safe use of wastewater in agriculture and aquaculture," emphasized quality thresholds for irrigating wastewater that were not realistic for developing countries without waste treatment plants. Besides, millions of farmers were already applying wastewater to their lands. They advocated paying more attention to livelihood issues while designing alternative risk mitigation options. Hussain et al. (2002) reviewed wastewater use in agriculture. They discuss inclusion of waste stabilization ponds or constructed wetlands before the wastewater is used for irrigation. This is, of course, only when land is available. They also mention religious obstacles in Muslim countries to use "unclean" wastewater. When discussing soils, emphasis is on negative aspects: accumulation of salts, sodicity, and heavy metals. Positive effects of purifying percolating wastewater, adding good-quality water to the aquifer, and avoiding surface water pollution are not covered, nor are the beneficial effects of added nutrients and organic matter and reducing erosion risks. Currently, IWMI and other agencies are developing criteria for wastewater use in the context of the UN Sustainable Development Goals, building on their concept of "multiple barriers" defining risk-reducing measures, including an end to irrigation a few days before harvest, exposing waste to the sun, not touching leaves that were in contact with the waste, and drying of fecal waste before it is applied to the soil. So far, attention is very much focused on health and technical water aspects, while soils are hardly mentioned, implying that here we can hardly speak of an example of the waste-soil-water Nexus because of limited attention for soils.

8.6 Applying Dairy Factory Wastewater in New Zealand

Several studies have been made in New Zealand following application of dairy factory wastewater to land. An example is the work of Liu and Haynes (2010). They report effects of irrigation with dairy factory wastewater on soil properties at two sites that had received irrigation for >60 years. In comparison with paired sites that had not received effluent, long-term wastewater irrigation resulted in an increase in pH, EC, extractable P, exchangeable Na and K, and ESP. These changes were related to the use of phosphoric acid, NaOH, and KOH as cleaning agents in the factory. Despite these clear changes in soil chemical properties, there were no increases in soil organic matter content (organic C and total N). The size (microbial biomass C and N) and activity (basal respiration) of the soil microbial community did, however, increase by wastewater irrigation. These increases were attributed to regular inputs of soluble C (e.g., lactose) present as milk residues in the wastewater. Other studies reported comparable results with overall positive conclusions about soil quality (e.g., Degens et al. 2000). In these studies, emphasis was on static soil properties, and no comments were made on the purifying action of the soil resulting in favorable groundwater recharge or on possible effects on trafficability. This study is a good example of the waste-soil-water Nexus, again with a direct focus on the application of wastewater on soils without considering possible alternative procedures.

8.7 Wastewater Treatment in Rural Areas in Hungary and in the EU

Somogyi et al. (2009) reviewed the status of on-site wastewater treatment systems in Hungary and in the European Union. They conclude that decentralized on-site wastewater treatment systems (WWTS) become a real alternative to the centralized way of wastewater treatment. These small-scale units have high priority in low-population-density areas, where discharge of sewage to a central treatment system is unfeasible if only because long drainage conduits are too costly and stagnant wastewater will cause technical problems. The European Council Directive 91/271/EEC (EEC 1991) concerning urban wastewater treatment states that where wastewater collection systems are not justified either because of economic or environmental reasons, individual systems should be used. In Hungary, this is very difficult because many areas are not suitable because of soil conditions and there are no inspectors who can evaluate site suitability. The reuse of treated wastewater is not regulated either and so there is a big gap here between what is indicated in the rules and regulations and what is realistically feasible in practice. Comparable situations occur in other European countries.

Of the total number of settlements in Central and Eastern Europe (CEE), 90 % have less than 2000 inhabitants (Bodík and Ridderstolpe 2008), corresponding with 20 % of the CEE population and 4 % of Europe's population. The perspective until 2015 is that 75–90 % of the total CEE population will become connected to centralized systems of sewerage and wastewater treatment. This leaves a gap of 10–15 % of the people or 20 million rural inhabitants. Since there is no legal framework for wastewater treatment in those settlements, there is a risk of neglecting the problem which may lead to unnecessary health problems and environmental pollution. The European Council Directive 91/271/EEC (EEC 1991) concerning urban wastewater treatment states that "Treated wastewater shall be reused whenever appropriate." The problem is that the term "appropriateness" remains legally undefined, offering no perspective for effective action. Conditions in other European countries differ, but in general attention for on-site waste disposal is either lacking or inadequate.

The Swedish framework for regulation of on-site treatment systems was updated in 2006 and 2008 (Buitenkamp and Richert-Stintzing 2008). One specification is that on-site systems need to reduce BOD7 and phosphorus by 90 % and nitrogen by 50 % in sensitive areas, whereas systems in other areas must reduce BOD7 and phosphorus by 90 % and 70 %, respectively (Weiss et al. 2008). Despite the strict limits, many conventional on-site wastewater treatment systems in Sweden do not meet these requirements (Buitenkamp and Richert-Stintzing 2008). Again, there is a big gap between the regulations on the one hand and the practical implementation and control on the other. Besides, legislation appears to focus on the composition of the wastewater which is not improved by the septic tanks, as such, but by percolation through the soils. In fact, the improvement of wastewater quality is ideally achieved at a certain depth below the soil surface, and this is not measured nor defined in the regulations. Many private households will need to improve their treatment systems, and it is unclear how this can be achieved in practice.

In Finland, approximately one million residents (around 19 % of the population; see www.vaestorekiaterikeskm.fi) and over one million vacationers are active outside the municipal sewer network (Santala 2007). In rural areas, the discharge of phosphorus to surface water is 50 % higher than in urban areas (Ruokojärvi 2007), as lack of rural wastewater treatment is directly connected to eutrophication. This needs to be considered in planning water management and restoration processes, but it is not at the present time. One interesting point of the Finnish regulation is that the use of dry toilets is encouraged, reducing the volume of the waste (Santala 2007).

The University of Brighton reported that approximately 98 % of UK households are connected to a central sewerage network (Dee and Sivil 2001). The majority of municipal wastewater from both urban and rural areas is therefore purified in central wastewater treatment plants. In the UK, water supply and wastewater industries are privately owned since 1989, and the profit motive is therefore a very important aspect in the UK. The distribution of the unconnected 2 % of households is currently unknown, but many of these properties are most probably situated in rural areas. Of the non-main systems, 77 % treats wastewater in septic tanks, 14 % has package plants, and 9 % is unknown.

Finally, 96 % of Hungary's surface water originates from neighboring countries. Due to this fact, the quality and quantity of the Hungarian water bodies depend to a significant extent on the actions of surrounding countries. However, local industrial and agricultural pollution contributes to the contamination as well, and untreated or not well-treated sewage plays a significant role in the pollution load of the water supply. Since more than 90 % of drinking water originates from groundwater, its protection is a strategic task in Hungary. In Hungary, the proportion of settlements with less than 2000 inhabitants is high (75 %), but only 17 % of the population lives there (Min. Env. Prot. Water, 2008). The proportion of households in areas with no available sewerage system is 25 %. The proportion of Hungary's wastewater flow from these settlements is therefore only 4.7 %. Still, the effects of pollution on surface water and groundwater are significant, and development of reliable on-site treatment facilities needs the kind of priority it does so far not receive. Such a development would benefit by following a waste-soil-water Nexus approach.

9 The State of the Art

Taking a Nexus view of the relations between waste, soil, and water, the three elements are not well balanced at this moment in time. The waste component, both solid and liquid, has been very well documented in terms of its composition, generation, and disposal requirements. The quality of surface water and groundwater is well defined, and hydrological models are available to characterize the hydrological dynamics of fields, watersheds, and regions. Often soils are, however, poorly represented in these models, but as so many factors play a role in determining hydrologic regimes of areas of land, one has to be careful to rapidly conclude that more attention for soil input would improve the hydrological modeling results. We simply don't know. Modern monitoring equipment, including proximal and remote sensing techniques, has strongly improved the capacity to validate hydrological model outputs that are currently often validated on the basis of very limited base flow data. This validation procedure needs to be improved, and this can, in turn, result in acknowledging the need to incorporate modern soil data in hydrological models if it turns out to provide better modeling results. Modeling is crucial to express the spatial effects of waste application at a given site and becomes even more important when effects of climate change have to be considered when exploring future land-use scenarios.

As soon as waste, in the form of compost or as wastewater, reaches the soil, the understanding of the associated dynamic soil processes appears to be rather limited. These processes occur in unsaturated soil which is important, if not crucial, for purification as has been discussed earlier. The delicate balance between the desired relatively high flow rates that restrict the size of seepage beds on the one hand and the needed relatively low flow rates in unsaturated soil to achieve purification, on the other, is a key factor for liquid waste disposal on soil. And every soil has a specific balance. Just mentioning "soils" in general and only considering *Ksat* is not adequate. Few studies, aside from Bouma (1979), appear to have systematically applied unsaturated flow theory to liquid waste disposal on soils, and this presents a basic problem to be focused on by hydropedologists.

Urban or agricultural wastewater has been successfully applied to soils for many years in, for example, Braunschweig, Germany, and in New Zealand, but soil processes are only documented in general terms or in terms of static soil characteristics. Also, in many studies, the positive effect of feeding the groundwater aquifer with purified water is not mentioned even though this is very important for future applications because water shortages as a result of excessive use or future climate change are widely considered to offer major problems.

Little attention for soil processes and soil diversity also appears to occur when adding compost, where manuals only emphasize compost generation, composition, and application procedures. An identical impression is formed when studying the papers presented in the timely recent SSSA conference on on-site liquid waste disposal. There is little attention to unsaturated flow phenomena and soil diversity. There appears to be a discrepancy between soil classification on the one hand, defining many different types of soil, and the description of processes describing application of waste be it liquid or solid. It seems that when discussing waste application, *a soil is a soil is a soil*. But already in 1979, we documented the essentially different behaviors of sands, silts, and clays when accepting liquid waste. Every soil type "has a story to tell." This, again, presents a challenge for hydropedology to "assist the soil to make her voice audible."

An additional comment as to what happens after application of waste to the soil is the perceived lack of a broad perspective on the effects on overall management. For example, adding compost successfully implies that the organic matter content of the soil increases and this is favorable because of a higher moisture supply capacity, carbon mitigation, and a higher adsorptive capacity. But the higher moisture contents can also result to a higher compatibility (Droogers et al. 1996), and this can have adverse effects on soil productivity and lead to runoff and erosion, the more so since modern agriculture increasingly uses heavy machinery. Advantages and disadvantages have therefore to be balanced in studies that cover the complete production system and not only part of it. And, again, relationships between organic matter and water content of soil on the one hand and the compatibility on the other are quite different for different soils, also as a function of their position in a landscape which often strongly impacts their water regimes. Consideration of the entire agricultural production and management chain is important to communicate effectively with stakeholders, and few studies take this complete approach or allude to it.

Overall, the Nexus approach is quite valuable in clarifying relationships between waste, water, and soil in defining a proper balance between the three elements. This position paper concludes that more attention is needed for dynamic soil processes in different soils that are associated with applying waste to soil. There is a clear imbalance between the amount of information available for waste and water at zero or positive pressure, occurring in groundwater and streams, as compared with soil and water in unsaturated conditions that are crucial for transformation and incorporation of compost and for liquid waste acceptance and purification.

10 Recommendations

1. Studies of the waste-soil-water Nexus are often restricted to adding waste to soil and measuring effects on soil and water by static indicators. A true Nexus approach would require a broader, dynamic societal focus considering alternative ”options,” including the entire waste generation chain, dynamic soil processes, and water regimes in soils and landscapes.
2. When studying the waste-soil-water Nexus, a balanced approach should be taken in which the three constituting elements of the Nexus receive a comparable degree of attention.
3. Dynamic and interrelated physical, chemical, and biological soil processes play a key role in waste transformation, particularly in unsaturated soil. These processes need more attention in research.
4. Many studies on waste disposal on soil emphasize negative aspects of the waste-soil-water Nexus in terms of water pollution and soil degradation. More attention is needed for potentially favorable effects such as improved soil and water quality, feeding of the aquifer, reduction of erosion, and increased biomass production.
5. Socioeconomic conditions need more emphasis in future work. Much can be achieved by applying existing knowledge, but implementation is too often lacking because stakeholders are indifferent. The Nexus approach not only calls for interdisciplinary but also for transdisciplinary approaches and for innovative communication.

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