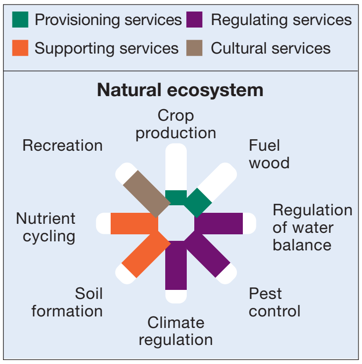

Natural ecosystem services

Artist: Peter Grundy, United Kingdom

6 Agriculture, water, and ecosystems: avoiding the costs of going too far

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Overview

Agricultural systems depend fundamentally on ecological processes and on the services provided by many ecosystems. These ecological processes and services are crucial for supporting and enhancing human well-being. Ecosystems support agriculture, produce fiber and fuel, regulate freshwater, purify wastewater and detoxify wastes, regulate climate, provide protection from storms, mitigate erosion, and offer cultural benefits, including significant aesthetic, educational, and spiritual benefits.

Agricultural management during the last century has caused widescale changes in land cover, watercourses, and aquifers, contributing to ecosystem degradation and undermining the processes that support ecosystems and the provision of a wide range of ecosystem services. Many agroecosystems have been managed as though they were disconnected from the wider landscape, with scant regard for maintaining the ecological components and processes that underpinned their sustainability. Irrigation, drainage, extensive clearing of vegetation, and addition of agrochemicals (fertilizers and pesticides) have often altered the quantity and quality of water in the agricultural landscape. The resultant modifications of water flows and water quality have had major ecological, economic, and social consequences, including effects on human health *[well established]*. Among them are the loss of provisioning services such as fisheries, loss of regulating services such as storm protection and nutrient retention, and loss of cultural services such as biodiversity and recreational values. Adverse ecological change, including land degradation through pollution, erosion, and salinization, and the loss of pollinators and animals that prey on pest species, can have negative feedback effects on food and fiber production *[well established]*. In extreme cases human health can also suffer, for example, through insect-borne disease or through changes in diet and nutrition. All too often the consequences of modifying agroecosystems have not been fully considered nor adequately monitored.

It has been increasingly recognized that agricultural management has caused some ecosystems to pass ecological thresholds (tipping points), leading to a regime change in the ecosystem and loss of ecosystem services. Ecosystem rehabilitation is likely to be costly, if possible at all. Some changes can be nearly irreversible (for example, the establishment of anoxic areas in marine water bodies). These changes can occur suddenly, although they often represent the cumulative outcome of a slow decline in biodiversity and reduced ecological resilience (the ability to undergo change and retain the same function, structure, identity, and feedbacks).

An integrated approach is needed for managing land, water, and ecosystems that acknowledges the multifunctionality of agroecosystems in supporting food production and ecosystem resilience

The poor people in rural areas who use a variety of ecosystem services directly for their livelihoods are likely to be the most vulnerable to changes in ecosystems. Therefore, failure to tackle the loss and degradation of ecosystems, such as that caused by the development and management of agriculture-related water resources, will ultimately undermine progress toward achieving the Millennium Development Goals of reducing poverty, combating hunger, and increasing environmental sustainability.

An integrated approach is needed for managing land and water resources and ecosystems that acknowledges the multifunctionality of agroecosystems in supporting food production and ecosystem resilience. That requires a better understanding of how agroecosystems generate multiple ecosystem services and of the value of maintaining biodiversity, habitat heterogeneity, and landscape connectivity in agricultural landscapes. Social issues, such as the importance of the role of gender in management decisions, also require more emphasis. Attention should be directed toward minimizing the loss of ecosystem resilience and building awareness of the importance of cumulative changes and of extreme events for generating ecosystem change. It is also necessary to meet the water requirements for sustaining ecosystem health and biodiversity in rivers and other aquatic ecosystems (marshes, lakes, estuaries) and to demonstrate the benefits of these services to society as a whole.

It has been estimated that by 2050 food demand will roughly double. As populations and incomes increase, demand for water allocations for agriculture will rise. Simplified, there are three main ways in which this increased water requirement can be met: through increased water use on current agricultural lands, through expansion of agricultural lands, and through increased water productivity. While all are plausible and a mix of solutions is likely, each has vastly different implications for nonagricultural ecosystems and the services they generate.

With the current high levels of land conversion and river regulation globally, greater consideration should be given to improving management of water demand within existing agricultural systems, rather than seeking further expansion of agriculture. Dependent on local conditions, technologies and management practices need to be substantially improved, and ecologically sound techniques implemented more widely to reduce the impacts from agriculture, whether extensive or intensive. Further intensification will require careful management to prevent further degradation and loss of ecosystem services through increased external effects and downstream water pollution. With the basis of many essential ecosystem services already seriously undermined, there is an urgent need not only to minimize future impacts, but also to reverse loss and degradation through rehabilitation and, in some cases, full restoration.

An integrated approach to land, water, and ecosystems at basin or catchment scale is urgently needed to increase multiple benefits and to mitigate detrimental impacts among ecosystem services. This involves assessing the costs and benefits as well as all known risks to society as a whole and to individual stakeholders. Societally accepted tradeoffs are unlikely without wide stakeholder discussion of consequences, distribution of costs and benefits, and possible compensation. It is also important that the results feed into processes of social learning about ecosystem behavior and management. A few tools are available to assist in striking tradeoffs (including economic valuation and desktop procedures for establishing environmental flows), but more efficient and less sectorally specific tools are needed. Most of the tools were developed to enable better decisionmaking on well known problems and benefits. Needed are tools to address the lesser known problems and benefits and to prepare for surprises.

There is a need not only to minimize future ecosystem impacts, but also to reverse loss and degradation through rehabilitation and, in some cases, full restoration

Decisions on tradeoffs under uncertain conditions should be based on a set of alternative scientifically informed arguments, with an understanding of the uncertainties that exist when dealing with ecological forecasting. To minimize the sometimes very high future costs of unexpected social and ecological impacts, it will be necessary to conceptualize uncertainty in decisionmaking. Adaptive management and scenario planning that improve assessment, monitoring, and learning are two components of this conceptualization.

Ongoing attention is required to communicate ecological messages across disciplinary and sectoral boundaries and to relevant policy and decisionmaking levels. The challenge is to produce simple messages about the multiple benefits of an ecosystem and about how ecosystems generate services—without oversimplifying the complexity of ecosystems.

In view of the huge scale of future demands on agriculture to feed humanity and eradicate hunger, and the past undermining of the ecological functions on which agriculture depends, it is essential that we change the way we have been doing business. To do this, we need to:

- Address social and environmental inequities and failures in governance and policy as well as on-ground management.
- Rehabilitate degraded ecosystems and, where possible, restore lost ecosystems.
- Develop institutional and economic measures to prevent further loss and to encourage further changes in the way we do business.
- Increase transparency in decisionmaking about agriculture-related water management and increase the exchange of knowledge about the consequences of these decisions. In the past many changes in ecosystem services have been unintended consequences of decisions taken for other purposes, often because the tradeoffs implicit in the decisionmaking were not transparent or were not known *[well established]*.

Water and agriculture—a challenge for ecosystem management

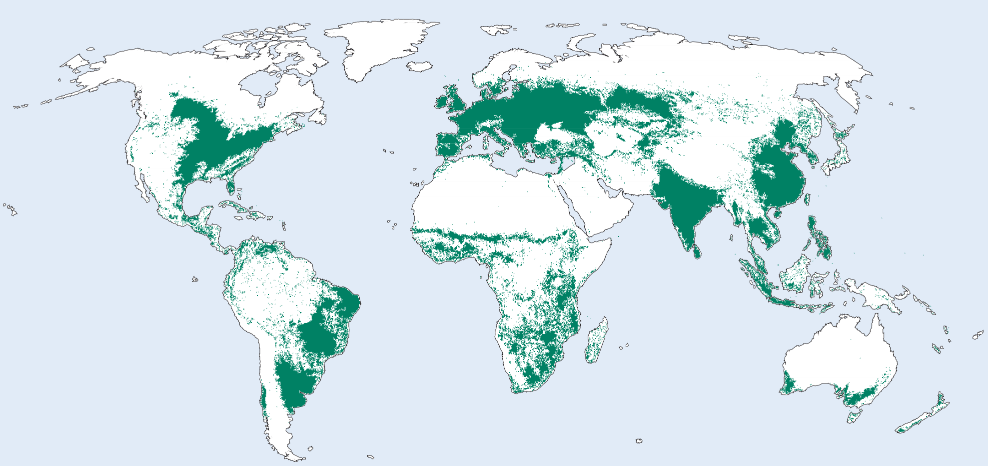
Changes in agriculture over the last century have led to substantial increases in food security through higher and more stable food production. However, the way that water has been managed in agriculture has caused widescale changes in land cover and watercourses, contributed to ecosystem degradation, and undermined the processes that support ecosystems and the provision of a wide range of ecosystem services essential for human well-being.

The Millennium Ecosystem Assessment, an international assessment by more than 1,300 scientists of the state of the world's ecosystems and their capacity to support human well-being, identified agricultural expansion and management as major drivers of ecosystem loss and degradation and the consequent decline in many ecosystem services and human well-being (www.maweb.org). Analyses illustrated that by 2000 almost a quarter of the global land cover had been converted for cultivation (map 6.1), with cropland covering more than 50% of the land area in many river basins in Europe and India and more than 30% in the Americas, Europe, and Asia. The Millennium Ecosystem Assessment also showed that the development of water infrastructure and the regulation of rivers for many purposes, including agricultural production, often resulted in the fragmentation of rivers (map 6.2) and the impoundment of large amounts of water (figure 6.1; Revenga and others 2000; Vörösmarty, Lévêque, and Revenga 2005).

Many scientists argue that as a society we are becoming more vulnerable to environmental change (Steffen and others 2004; Holling 1986), reducing our natural capital and degrading options for our current and future well-being (Jansson and others 1994; Arrow and others 1995; MEA 2005c). Natural and human-induced disasters, such as droughts and famine, are also likely to increase the pressure on vulnerable people, such as the rural poor, who depend most directly on their surrounding ecosystems (Silvius, Oneka, and Verhagen 2000; WRI and others 2005; Zwarts and others 2006).

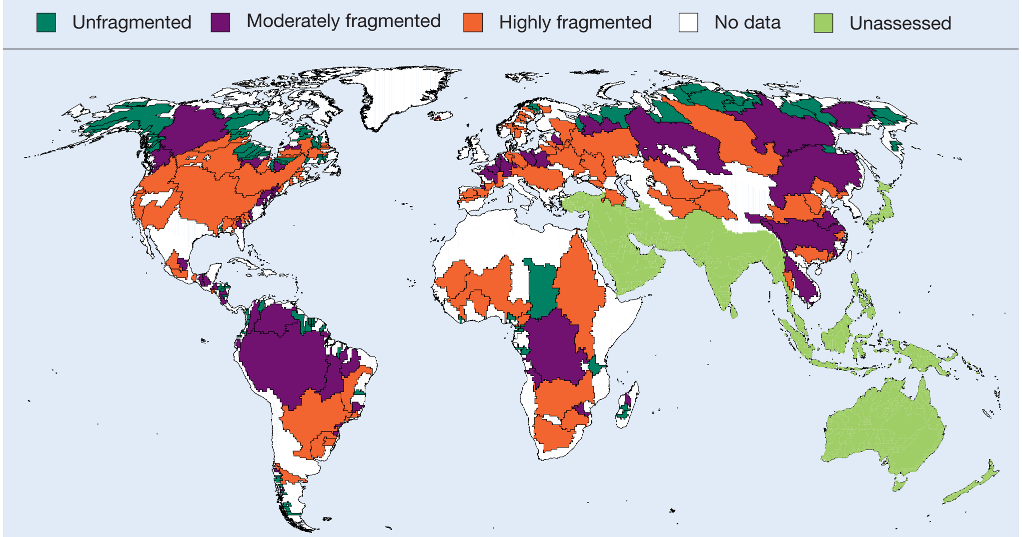
Furthermore, as populations and incomes grow, it has been estimated that food demand will roughly double by 2050 and shift toward more varied and water-demanding diets, increasing water requirements for food production (see chapter 3 on scenarios).

map **6.1** | **Extent of cultivated systems in 2000**



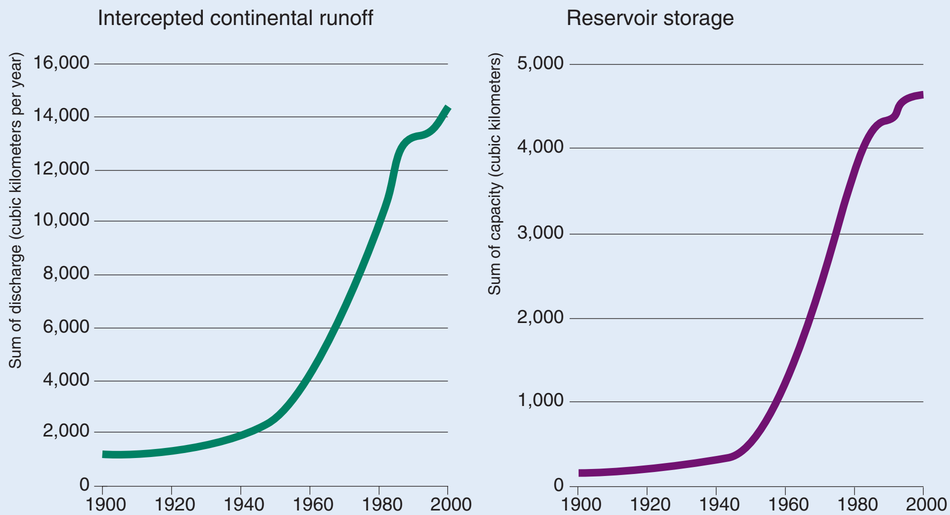
Note: Cultivated systems are defined as areas where at least 30% of the landscape is in croplands, shifting cultivation, confined livestock production, or freshwater aquaculture.
Source: MEA 2005c.

map **6.2** River channel fragmentation and flow regulation of global rivers



Source: Revenga and others 2000.

figure **6.1** Development of water infrastructure and regulation of rivers resulted in the impoundment of large amounts of water



Note: The time series data are taken from a subset of large reservoirs (0.5 cubic kilometers maximum storage each), geographically referenced to global river networks and discharge.

Source: Millennium Ecosystem Assessment.

Simplified, there are three main ways to meet this water requirement: increasing water use on current agricultural lands through intensification of production (see chapters 8 on rainfed agriculture and 9 on irrigation), expanding agricultural lands, and increasing water productivity (see chapters 7 on water productivity and 15 on land).

These options have vastly different implications for ecosystems and the services they generate. Increased water use on agricultural lands through irrigation will reduce the availability of blue water resources (surface water and groundwater), especially for downstream aquatic systems, and can contribute to waterscape alterations, for example, through the introduction of dams for irrigation. Increased green water flows (soil moisture generated from rainfall that infiltrates the soil) through higher consumptive water use in rainfed agriculture (as a result of increased crop productivity) will also reduce the availability of water downstream, although the extent to which this could occur varies *[established but incomplete]*. Expanding agricultural land can alter the water flow in the landscape, with impacts on terrestrial and aquatic ecosystems. Finally, while increased water productivity is intended to produce more food without using more water, it can lead to deterioration in water quality through increased use of agrochemicals.

> Humanity is facing an enormous challenge in managing water to secure adequate food production without undermining the life support systems on which society depends

Humanity is facing an enormous challenge in managing water to secure adequate food production without undermining the life support systems on which society depends—and in some instances while simultaneously rehabilitating or restoring those systems. Research on ecosystems has generally been separate from research on water in agriculture, leading to a segregated view of humans and food security on one side and nature conservation on the other. In this chapter we challenge this view by describing recent understanding of how all ecosystems support human well-being, including ensuring food security and redressing social inequities.

We focus on the links between ecosystems and management of water in agriculture. Water functions as the "bloodstream of the biosphere" (Falkenmark 2003). It is vital for the generation of many ecosystem services in both terrestrial and aquatic ecosystems and provides a link between ecosystems, including agroecosystems. As for agricultural production, we consider the importance of both blue and green water (see chapter 1 on setting the scene) for ecosystems, both those characterized by the presence of blue water, such as marshes, rivers, and lakes, and terrestrial ecosystems that depend on and modify green water.

We first assess the ecosystem effects of past water-related management in agriculture, highlighting some of the often unintentional tradeoffs between water for food production and water for other ecosystem services. We then outline response options for improving water management. We emphasize the need to intentionally deal with the unavoidable and often surprising tradeoffs that arise when making decisions to increase food production, noting that these are often embedded within complex social situations where different stakeholders have highly diverse interests, skills, and influence (see, for example, chapters 5 on policies and institutions, 15 on land, and 17 on river basins).

Agriculture and ecosystems

While agricultural production is driven by human management (soil tillage, irrigation, nutrient additions), it is still influenced by the same ecological processes that shape and drive nonagricultural ecosystems, particularly those that support biomass production and others such as nitrogen uptake from the atmosphere and pollination of crops. Agricultural systems are thus viewed as ecosystems that are modified, at times highly, by activities designed to ensure or increase food production (box 6.1). These ecosystems are often referred to as agroecosystems; the difference between an agroecosystem and other ecosystems is considered to be largely conceptual, related to the extent of human intervention or management.

Disruption of the processes that maintain the structure and functioning of an ecosystem, such as water flow, energy transfer, and growth and production, can have dire consequences, including soil erosion and loss of soil structure and fertility. Severe disruption can result in the degradation or loss of the agroecosystem itself or other linked ecosystems and the ecosystem services that it supplies (see chapter 15 on land). The degradation of the Aral Sea is a dramatic example of human intervention having gone too far (box 6.2).

box 6.1 | Agriculture makes landscape modifications unavoidable

There are many land and water manipulations that can increase the productivity of agricultural land in order to meet increasing demands for more food. All have consequences for ecosystems. The key message is that agriculture makes landscape modification unavoidable, although smarter application of technology and more emphasis on ecosystemwide sustainability could reduce adverse impacts. These land and water manipulations include:

- *Shifting the distribution of plants and animals.* Most apparent are the clearing of native vegetation and its replacement with seasonally or annually sown crops, and the replacement of wild animals with domestic livestock.
- *Coping with climate variability to secure water for crops.* As water is a key material for photosynthesis, crop productivity depends intimately on securing water to ensure growth. Three different time scales need to be taken into account when considering water security: seasonal shortfalls in water availability that can be met by irrigation so that the growing season is extended and extra crops can be added; dry spells during the wet season that can be met by specific watering that can be secured, even in small-scale farming, if based on locally harvested rain; and recurrent drought that has traditionally been met by saving grain from good years to rely on during dry years.
- *Maintaining soil fertility.* The conventional way to secure enough air in the root zone is by drainage and ditching through plowing to ensure that rain water can infiltrate. However, this also leads to erosion and the removal of fertile soil by strong winds and heavy rain. These side effects can be limited by focusing on soil conservation actions, such as minimum tillage practices.
- *Coping with crop nutrient needs.* The nutrient supply of agricultural soils is often replenished through the application of manure or chemical fertilizers. Ideally, the amount added should balance the amount consumed by the crop, to limit the water-soluble surplus in the ground that may be carried to rivers and lakes.
- *Maintaining landscape-scale interactions.* When natural ecosystems are converted to agricultural systems, some ecological processes (such as species mobility and subsurface water flows) that connect parts of the landscape can be interrupted. This can have implications for agricultural systems as it can affect pest cycles, pollination, nutrient cycling, and water logging and salinization. Managing landscapes across larger scales thus becomes important; an increasing number of studies illustrate how to design landscapes to increase the productivity of agriculture while also generating other ecosystem services (Lansing 1991; Cumming and Spiesman 2006; Anderies 2005; McNeely and Scherr 2003).

It is thus important to adapt agricultural management (including crop types) to the ecological conditions. Growing crops unsuited to the climate conditions, for example, could have harmful consequences. When agricultural techniques that had been developed in the temperate climate of Europe were introduced in late 18th century Australia, the result was vast areas of salinized lands (Folke and others 2002). Trying to grow lucrative oil palms on saline soils in the Indus Delta and Pakistan and the acid sulphate soils of Southeast Asia is another example of a severe mismatch between agricultural activity and ecological conditions. In the 1970s it was argued that there was a climate bias—"water blindness"—that led to efforts to transfer inappropriate agricultural technology from developed to developing countries (Falkenmark 1979).

Human well-being and ecosystem services

The Millennium Ecosystem Assessment (MEA 2005c) showed that the well-being of human society was intimately linked to the capacity of ecosystems to provide ecosystem services and that securing multiple ecosystem services depended on healthy ecosystems.

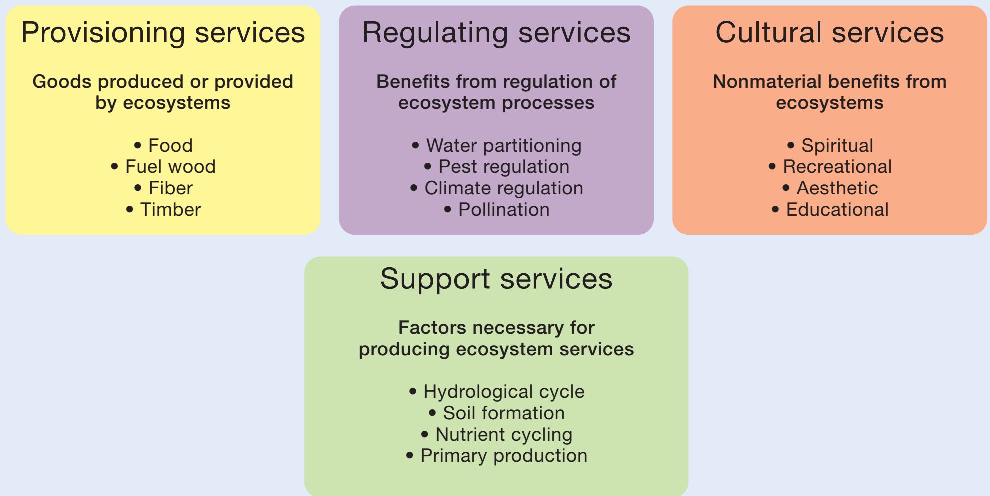
box 6.2 | The Aral Sea—an ecological catastrophe

The Aral Sea is probably the most prominent example of how unsustainable water management for agriculture has led to a large-scale and possibly irreversible ecological and human disaster. Reduced water flow in the rivers supplying the sea has resulted in outcomes that have impaired human livelihoods and health, affected the local climate, and reduced biodiversity. Since 1960 the volume of water in the Aral Sea Basin has been reduced by 75%, due mainly to reduced inflows as a consequence of irrigation of close to 7 million hectares of land (UNESCO 2000; Postel 1999). This has led to the loss of 20 of 24 fish species and collapse of the fishing industry; the fish catch fell from 44,000 tons annually in the 1950s to zero, with the loss of 60,000 jobs (Postel 1996). Species diversity and wildlife habitat have also declined, particularly in the wetlands associated with the sea (Postel 1999). The water diversions together with polluted runoff from agricultural land have had serious human health effects, including an increase in pulmonary diseases as winds whipped up dust and toxins from the exposed sea bed (WMO 1997).

Wind storms pick up some 100 million tons of dust containing a mix of toxic chemicals and salt from the dry sea bed and dump them on the surrounding farmland, harming and killing crops as well as people (Postel 1996). The low flows into the sea have concentrated salts and toxic chemicals, making water supplies hazardous to drink (Postel 1996). In the Amu Darya River Basin chemicals such as dichlorodiphenyl-trichloroethane (DDT), lindane, and dioxin have been carried by agricultural runoff and spread through the aquatic ecosystems and into the human food chain. Secondary salinization is also occurring (Williams 2002).

Attempts to rehabilitate the Northern Sea are under way through the Syr Darya and Northern Aral Sea Project (www.worldbank.org.kz); initial results are seen as positive (Pala 2006). A dam has been constructed between the two parts of the sea to allow the accumulation of water and to help rehabilitate parts of the delta. While the project aims to reestablish and sustain fishery and agricultural activities and to reduce the harmful effects on the drinking water, the extent of past changes makes restoration highly unlikely. The ecological and social changes in the Aral Sea ecosystem are considered largely irreversible.

figure **6.2** | **Types of ecosystem services**



Source: Adapted from MEA 2003.

Whether an ecosystem is managed primarily for food production, water regulation, or for other services (figure 6.2), it is possible to secure these for the long term only if basic ecosystem functioning is maintained. In many agroecosystems considerable effort goes into ensuring crop production, but often at the expense of other important services, such as fisheries (Kura and others 2004), freshwater supply (Vörösmarty, Lévêque, and Revenga 2005), and regulation of floods (Daily and others 1997; Bravo de Guenni 2005).

Biodiversity—variability and diversity within and among species, habitats, and ecosystem services—is important for supporting ecosystem services and has value in its own right. Further, biodiversity can act as an insurance mechanism by increasing ecosystem resilience (box 6.3). Some species that do not seem to have an important role in ecosystems under stable conditions may be crucial in the recovery of an ecosystem after a disturbance. Similarly, if one species is lost, another with similar characteristics may be able to replace it. While the concept of biodiversity comprises ecosystems, species, and genetic components, most of the discussion in this chapter focuses on the functional role of ecosystems and species (or taxa) in terms of the ecosystem services that they provide.

There is increasing evidence that ecosystems play an important role in poverty reduction (Silvius, Onela, and Verhagen 2000; WRI and others 2005). Many rural poor people rely on a variety of sources of income and subsistence activities that are based on ecosystems and are thus most directly vulnerable to the loss of ecosystem services *[established]*. These sources of income, often generated by women and children, include small-scale farming and livestock rearing, fishing, hunting, and collecting firewood and other ecosystem products that may be sold for cash or used directly by households. Floodplain wetlands, for example, support many human activities, including fisheries, cropping, and gardening (photos 6.1–6.3).

box **6.3** **Biodiversity and ecosystem resilience**

The decline of biodiversity globally, most severely manifested in freshwater systems (MEA 2005b), has renewed interest in ecosystem conservation and management and in the links between biodiversity and ecosystem functioning (Holling and others 1995; Tilman and others 1997), including the role in human well-being (MEA 2005c) and the links to poverty (Adams and others 2004; WRI and others 2005). Many people highlight the ethical argument for conserving biodiversity for its own intrinsic value, and projects aimed at conserving endangered species (establishment of protected areas, changed land-use practices) have been common investment strategies, with different social outcomes (Adams and others 2004).

Research in recent decades has illustrated the importance of species diversity for ecosystem functioning (see photos of wetland biodiversity). The general theory is that a more diverse system contributes to more stable productivity by providing a means of coping with variation.


Photo by C. Max Finlayson
Pelicans


Photo by Karen Conniff
Dragonfly


Photo by C. Max Finlayson
Crocodile


Photo by C. Max Finlayson
Elephants

However, it has recently been argued that it is not the richness of species that contributes to ecosystem functioning, but rather the existence of functional groups (predators, pollinators, herbivores, decomposers) with different and sometimes overlapping functions in relation to ecosystem processes (Holling and others 1995). To understand the role of diversity for ecosystem functioning, it is necessary to analyze the identities, densities, biomasses, and interactions of populations of species in the ecosystem, as well as their temporal and spatial variations (Kremen 2005). Diversity of organisms within and between functional groups can be critical for maintaining resistance to change.

Species that may seem redundant during some stages of ecosystem development may be critical for ecosystem reorganization after disturbance (Folke and others 2004). Response diversity (the differential responses of species to disturbance) helps to stabilize ecosystem services in the face of shocks (Elmqvist and others 2003).

Photo 6.1

Photo 6.2

Photo 6.3

Photos by C. Max Finlayson

Fisheries, cropping, and gardening are among the many human activities supported by floodplain wetlands.

The Millennium Ecosystem Assessment concluded that a failure to tackle the decline in ecosystem services will seriously erode efforts to reduce rural poverty and social inequity and eradicate hunger; this is a critical issue in many regions, particularly in Sub-Saharan Africa (WRI and others 2005). It is also true that continued and increasing poverty can intensify pressure on ecosystems as many of the rural poor and other vulnerable people are left with no options but to overexploit the remaining natural resource base. The result is often a vicious cycle in which environmental degradation and increased poverty are mutually reinforcing forces (Silvius and others 2003). The Millennium Ecosystem Assessment (MEA 2005c) concluded that interventions that led to the loss and degradation of wetlands and water resources would ultimately undermine progress toward achieving the Millennium Development Goals of reducing poverty and hunger and ensuring environmental sustainability.

Consequences and ecosystem impacts

Modifications of the landscape to increase global food production have resulted in increased provisioning services, but also in adverse ecological changes in many ecosystems, with concomitant loss and degradation of services (MEA 2005c). Water management has caused changes in the physical and chemical characteristics of inland and coastal aquatic ecosystems and in the quality and quantity of water, as well as direct and indirect biological changes (Finlayson and D'Cruz 2005; Agardy and Alder 2005; Vörösmarty, Lévêque, and Revenga 2005). It has also caused changes in terrestrial ecosystems through the expansion of agricultural lands and changes in water balances (Foley and others 2005).

These changes have had negative feedback on the food and fiber production activities of agroecosystems, for example through reductions in pollinators (Kremen, Williams, and Thorp 2002) and degradation of land (see chapter 15 on land) *[established but incomplete]*. Adverse changes have varied in intensity, and some are seemingly irreversible, or at least difficult or expensive to reverse, such as the extensive dead zones in the Gulf of Mexico and the Baltic Sea (Dybas 2005). The catastrophic collapse of coastal fisheries as a consequence of environmental change is another example (see chapter 12 on inland fisheries). This chapter focuses on the consequences for ecosystems of green and blue water management in agriculture while acknowledging that many other human activities also play a role. Synergistic and cumulative effects can make it extremely difficult to attribute change to a single cause (box 6.4).

box **6.4** **Cumulative changes—new challenges for water management in agriculture**

New challenges are emerging for water managers in agriculture as a consequence of the cumulative and sometimes synergistic effects of multiple drivers, including climate change and invasive species.

Global climate change is expected to directly and indirectly alter and degrade many ecosystems (Gitay and others 2002). For example, it will exacerbate problems associated with already expanding demand for water where it leads to decreased precipitation, while in limited cases, where precipitation increases, it could lessen pressure on available water. There are also major expected consequences for wetland ecosystems and species, although the extent of change is not well established (Gitay and others 2002; van Dam and others 2002; Finlayson and others forthcoming).

There is growing recognition of the important role that invasive species can play in degradation of ecosystems and ecosystem services (MEA 2005c). Invasive species, spread through water regulation for transport and water transfer and through trade, have altered the character of many aquatic ecosystems (see photo). Once established, invasive plants can block channels and irrigation canals and decrease connectivity within and between rivers and wetlands, replace valuable species, and damage infrastructure (Finlayson and D'Cruz 2005).

Invasive species from forest plantations are also threatening water supply for downstream users, as shown in South Africa where cities such as Cape Town and Port Elisabeth depend on runoff from the natural low biomass vegetation in the catchment (Le Maitre and others 1996). Invasive species in riparian areas are a problem for water resources in several other parts of the world. The annual losses due to the invasive woody species tamarisk in the semiarid western United States reach $280–$450 a hectare, with restoration costs of approximately $7,400 a hectare (Zavaleta 2000).


Photo by C. Max Finlayson

Water hyacinth, a rapidly growing, free-floating invasive plant, has degraded many ecosystems

Aquatic ecosystems

Water-related agricultural modifications have had major ecological, economic, and social consequences, including effects on human health, through changes in the key ecological components and processes of rivers, lakes, floodplains, and groundwater-fed wetlands *[well established]*. These changes include alterations to the quantity, timing, and natural variability of flow regimes; alterations to the waterscape through the drainage of wetlands and the construction of irrigation storages; and increased concentrations of nutrients, trace elements, sediments, and agrochemicals.

Aquatic ecosystems provide a wide array of ecosystem services *[well established]*. Their nature and value are not consistent, however, and our understanding of how ecosystem processes support many of these services is inadequate (Finlayson and D'Cruz 2005; Baron and others 2002; Postel and Carpenter 1997). In several areas around the world changes have contributed to a loss of provisioning services such as fisheries, regulating services such as storm protection and nutrient retention, and cultural services such as recreational and aesthetic uses. In some cases ecosystems have passed thresholds or gone through regime shifts leading to a collapse of ecosystem services, making the costs of restoration (if possible at all) very high. These losses have adverse effects on livelihoods and economic production *[well established]*. There is ongoing debate whether the positive outcomes in terms of increased upstream production of food outweigh the negative consequences for people dependent on downstream ecosystem services. While most cost-benefit studies show that the costs of the losses have been higher than the gains, other scientists argue that these studies have many weaknesses (Balmford and others 2002).

Long-term trend analysis of 145 major world rivers indicates that discharge has declined in one-fifth of cases

Although agriculture, especially water management in agriculture, is a major driver behind the loss of downstream ecosystem services *[well established]*, there are competing explanations for the manner and importance of individual processes and events and the ultimate role of agriculture as a triggering force for degradation is in many situations unknown. Dams, overfishing, urban water withdrawals, and natural and anthropogenic climate variation can contribute to cumulative and synergistic effects, reduced resilience, and increased degradation of downstream ecosystems (photo 6.4). Uncertainty is often high when it comes to the exact location or timing of the response of downstream ecosystems to upstream water alterations. This does not mean that we can ignore the role of agriculture. But we need to address the problems as complex and interacting, and to consider a systems perspective for analyzing multiple drivers of change.

The next two sections offer examples of how water-related management in agriculture has changed the capacity of downstream ecosystems to generate ecosystem services and a brief discussion of the consequences of some of these changes.

Water quantity and waterscape alterations. Increased cultivation in recent decades has resulted in increased diversion of freshwater, with some 70% of water now being used for agriculture and reaching as high as 85%–90% in parts of Africa, Asia, and the Middle

Photo by C. Max Finlayson

Photo 6.4 Dams provide many benefits for people, but also affect ecosystems by changing the hydrology and fragmenting rivers

East (Shiklomanov and Rodda 2003) *[well established]*. Regulation of the world's rivers has altered water regimes, with substantial declines in discharges to the ocean (Meybeck and Ragu 1997). Long-term trend analysis (more than 25 years) of 145 major world rivers indicates that discharge has declined in one-fifth of cases (Walling and Fang 2003). Worldwide, large artificial impoundments hold vast quantities of water and cause significant distortion of flow regimes (Vörösmarty and others 2003), often with harmful effects on human health (box 6.5).

Water diversion and the construction of hydraulic infrastructure (reservoirs, physical barriers) have altered downstream ecosystems through changes in the quantity and pattern of water flows and the seasonal inflows of freshwater (see global summaries in Vörösmarty, Lévêque, and Revenga 2005 and Finlayson and D'Cruz 2005). Negative effects include the loss of local livelihood options, fragmentation and destruction of aquatic habitats, changes in the composition of aquatic communities, loss of species, and health problems resulting from stagnant water. Less flooding means less sedimentation and deposition of nutrients on floodplains and reduced flows and nutrient deposition in parts of the coastal zone (Finlayson and D'Cruz 2005).

box **6.5** | **Water management and human health**

Many water-related diseases have been successfully controlled through water management (for example, malaria in some places), but others have been exacerbated by the degradation of inland waters through water pollution and changes in flow regimes (the spread of schistosomiasis). Where diseases have spread, the adverse effects on human health are due to a complex mix of environmental and social causes. The Millennium Ecosystem Assessment reported many instances where water management practices contributed to a decline in well-being and health (MEA 2005a; Finlayson and D'Cruz 2005). This includes diseases caused by the ingestion of water contaminated by human or animal feces; diseases caused by contact with contaminated water, such as scabies, trachoma, and typhus; diseases passed on by intermediate hosts such as aquatic snails or insects that breed in aquatic ecosystems, such as dracunculiasis and schistosomiasis, as well as dengue fever, filariasis, malaria, onchocerciasis, trypanosomiasis, and yellow fever; and diseases that occur when there is insufficient clean water for basic hygiene.

In addition to disease from inland waters, waterborne pollutants have a major effect on human health, often through their accumulation in the food chain. Many countries now experience problems with elevated levels of nitrates in groundwater from the large-scale use of organic and inorganic fertilizers. Excess nitrate in drinking water has been linked to methemoglobin anemia in infants.

There is increasing evidence from wildlife studies that humans are at risk from a number of chemicals that mimic or block the natural functioning of hormones, interfering with natural bodily processes, including normal sexual development. Chemicals such as DDT, dioxins, and those in many pesticides are endocrine disruptors, which may interfere with human hormone functions, undermining disease resistance and reproductive health.

The draining and burning of forested peat swamps in Southeast Asia have had devastating health effects (see box 6.6 later in this chapter) that extend across many countries and that may be long-lasting. The investigation of environment-related health effects linked with the ongoing degradation of the forested peat swamps is a major issue for health services in the region.

Interbasin transfers of water, particularly large transfers between major river systems as are being planned in India, for example, are expected to be particularly harmful to downstream ecosystems (Gupta and Deshpande 2004; Alam and Kabir 2004) and to exacerbate pressures from hydrological regulation (Snaddon, Davies, and Wishart 1999). Where these are being considered, scientific and transparent assessments of the benefits and problems are strongly encouraged. Junk (2002) has highlighted the similar adverse consequences on water regimes expected from the construction of industrial waterways (hidrovias) through large wetlands, such as the Pantanal of Maso Grosso, Brazil. The nature of expected changes depends on the amount and timing of water being transferred and so needs to be assessed case by case.

Worldwide, large artificial impoundments hold vast quantities of water and cause significant distortion of flow regimes, often with harmful effects on human health

Shrinking lakes. There are many instances where consumptive water use and water diversions have contributed to severe degradation of downstream ecosystem services. The degradation of the Aral Sea in Central Asia represents one of the most extreme cases (see box 6.2).

The desiccation of Lake Chad in West Africa is another example. It shrank from 25,000 square kilometers in surface area to one-twentieth that size over a 35-year period. However, there are competing explanations for this reduction. Natural rainfall variability is an important driver. The lake is very shallow, and at various times in its history it has assumed different states, with changes triggered by climate variability (Lemoalle 2003). It is unclear what role human-induced change has played, but different drivers include the withdrawal of irrigation water, land-use changes reducing precipitation through changes in albedo (the energy that is reflected by the earth and that varies with land surface characteristics), and reduced moisture recycling (Coe and Foley 2001).

Lake Chapala, the world's largest shallow lake, situated in the Lerma-Chapala Basin in central Mexico, is another example of consumptive water use upstream affecting the size of a lake. During 1979–2001 water volume in the lake dropped substantially to about 20% of capacity due to excessive water extraction for agricultural and municipal needs. Average annual rainfall from 1993 to 2003 was only 5% below the historical average and efforts were made to reduce water use in irrigation, but still the amount of surface and groundwater used in the basin exceeded supply by 9% on average (Wester, Scott, and Burton 2005). Above average rains in 2003 and 2004 increased the water volume to about 6,000 million cubic meters. There is still intense competition over water allocation, and environmental water requirements have yet to be determined, leaving the future of the lake and the allocation of water for urban and agricultural purposes under threat.

The high variability in lake volume in both Lake Chad and Lake Chapala means that the people depending on ecosystem services from these basins need to have a high adaptive capacity to cope with the rapidly changing circumstances, whether induced by people or nature.

Shrinking rivers. Consumptive use and interbasin transfers have transformed several of the world's largest rivers into highly stabilized and, in some cases, seasonally nondischarging, channels (Meybeck and Ragu 1997; Snaddon, Davies, and Wishart 1999; Cohen 2002). Streamflow depletion is a widespread phenomenon in tropical and subtropical regions in rivers with large-scale irrigation, including the Pangani (IUCN 2003), Yellow (He, Cheng, and Luo 2005), Aral Sea tributaries, Chao Phraya, Ganges, Incomati, Indus, Murray-Darling, Nile, and Rio Grande (Falkenmark and Lannerstad 2005). Smakhtin, Revenga, and Döll (2004) suggest that the streamflow required for aquatic ecosystem health (environmental flow) has already been overappropriated in many rivers.

In the United States the construction of dams and water diversions for irrigation and other purposes in the Colorado Basin, together with large-scale interbasin transfers, has greatly reduced the flow of the river to the delta. A considerable portion of the delta has been transformed into mudflats, saltflats, and exposed sand. With the loss of the delta habitats, wetlands now exist mainly in areas where agricultural drainage has occurred (Postel 1996). The Ganges is among the major rivers of South Asia that no longer discharge year round to the sea. As a result there is a rapid upstream advance of a saline front, with consequent changes in mangrove communities, fish habitat, cropping, and human livelihoods (Postel 1996; Mirza 1998; Rahman and others 2000). On the Zambezi River in Southern Africa damming for electricity and agriculture has reduced flows to the coast and led to a decline in shrimp production that could have been worth as much as $10 million a year (Gammelsrod 1992).

The regulation of rivers has brought many benefits, but the adverse impacts have often failed to receive adequate and transparent consideration

The regulation of rivers has brought many benefits to people, but the adverse impacts, especially those related to reduced downstream flows, have often failed to receive adequate and transparent consideration (WCD 2000; Revenga and others 2000; MEA 2005b).

Drainage of wetlands. Water regulation and drainage for agricultural development are the main causes of wetland habitat loss and degradation (Revenga and others 2000; Finlayson and D'Cruz 2005) and consequent loss of ecosystem services. By 1985 drainage and conversion of wetlands, mainly for agriculture, had affected an estimated 56%–65% of inland and coastal marshes in Europe and North America and 27% in Asia (OECD 1996). Drainage of wetlands often reduces important regulating ecosystem services, with such outcomes as increased vulnerability to storms and flooding and further eutrophication of lakes and coastal waters.

Harder to demonstrate is the cumulative effect of the loss of smaller sites, both individual sites and networks of sites, such as those used by migratory waterbirds (Davidson and Stroud forthcoming). The adverse effects are often assumed, but the evidence is incomplete. Still, there are many lessons, such as those from the drainage and subsequent burning of forested peat swamps in Southeast Asia (box 6.6), a case that has had dramatic health effects on many people across the region (see box 6.5). The loss of small wetlands (referred to as potholes) on the prairies of Canada and the United States through drainage and infilling has led to the loss of habitat for large numbers of migratory waterbirds (North American Waterfowl Management Plan 2004). The loss of forested riparian wetlands adjacent to the Mississippi River in the United States was seen as an important factor contributing to the severity and damage of the 1993 flood in the Mississippi Basin (Daily and others 1997).

Wetlands are often thought to act as "sponges" that soak up water during wet periods and release it during dry periods. While there are numerous examples of wetlands, notably floodplains, where this does occur, there is increasing evidence that such generalizations are not applicable for all hydrological contexts or wetland types (Bullock and Acreman

box 6.6 The widespread impacts of draining and burning in Southeast Asian peatlands

Large parts of the tropical peat swamp forests in Southeast Asia have been seriously degraded, largely due to logging for timber and pulp (Wösten and others 2006; Page and others 2002). The process has been accelerated over the last two decades by the conversion of forests to agriculture, particularly oil palm plantations. Drainage and forest clearing threaten the stability of large tracts of forests in Indonesia and Malaysia and make them susceptible to fire.

Attempts to clear and drain the forests and establish agriculture have high rates of failure. Under the Mega Rice Project in Kalimantan, Indonesia, large areas of forest were cleared and some 4,600 kilometers of drainage canals were constructed in an attempt to grow rice on a grand scale using emigrant workers from the heavily populated neighboring island of Java. The cleared land was unsuited to rice production, and the scheme was abandoned. In 1997 land clearing and subsequent uncontrolled fires severely burned about 5 million hectares of forest and agricultural land in Kalimantan, releasing an estimated 0.8–2.6 billion tons of carbon dioxide into the atmosphere (Glover and Jessup 1999; Page and others 2002; Wooster and Strub 2002). The fires created a major atmospheric haze, with severe impacts on the health of 70 million people in six countries. In addition, there have been economic effects on timber and agricultural activities, with the fires compounding the loss of peatlands through clearing and failed attempts to cultivate large areas for rice.

Rehabilitation of some degraded areas is under way, but it is a slow and difficult process trying to reestablish the hydrology and vegetation (Wösten and others 2006). At a regional level the Association of Southeast Asian Nations (ASEAN) has taken an active interest in the problem through the ASEAN Peatland Management Initiative, facilitating the sharing of expertise and resources among the affected countries to prevent peatland fires and manage peatlands wisely. The regional initiatives are linked with national action plans. Monitoring mechanisms are in place, and a policy of zero burning for further land clearing has also been established, in particular for oil palm plantations.

Despite these steps, the problem of peatland degradation continues. The expansion of oil palm plantations is a major driver. The peat swamps are still being cleared and burned, undermining efforts to conserve and use the peatlands of Southeast Asia wisely and threatening the health of people locally and regionally.

2003). Indeed, there are instances where the opposite occurs: where wetlands reduce low flows, increase floods, or act as a barrier to groundwater recharge. Given the wide range of wetlands, from entirely groundwater-fed springs and mountain bogs to large inland river floodplains, such variation should not be surprising.

Changes in water quality. Many factors contribute to changes in water quality. This section looks at nutrient loads, agrochemicals, and siltation.

Nutrient loading. The use of fertilizers has brought major benefits to agriculture, but has also led to widespread contamination of surface water and groundwater through runoff. Over the past four decades excessive nutrient loading has emerged as one of the most important direct drivers of ecosystem change in inland and coastal wetlands, with the flux of reactive nitrogen to the oceans having increased by nearly 80% from 1860 to 1990 (MEA 2005c). Phosphorus applications have also increased, rising threefold since 1960, with a steady increase until 1990 followed by a leveling off at approximately the application rates of the 1980s (Bennett, Carpenter, and Caraco 2001). These changes are mirrored by phosphorus accumulation in soils, with high levels of phosphorus runoff. In developed countries annual storage peaked around 1975 and is now at about the same annual rate as in 1961. In developing countries, however, storage went from negative values in 1961 to about 5 teragrams per year in 1996.

Excessive nutrient loading can cause algal blooms, decreased drinking water quality, eutrophication of freshwater ecosystems and coastal zones, and hypoxia in coastal waters. In Lake Chivero, Zimbabwe, agricultural runoff is seen as responsible for algal blooms, infestations of water hyacinth, and fish declines as a result of high levels of ammonia and low oxygen levels (UNEP 2002). In Australia extensive algal blooms in coastal inlets and estuaries, inland lakes, and rivers have been attributed to increased nutrient runoff from agricultural fields (Lukatelich and McComb 1986; Falconer 2001). Diffuse runoff of nutrients from agricultural land is held to be largely responsible for increased eutrophication of coastal waters in the United States as well as for the periodic development, often varying from year to year, of anoxic conditions in coastal water in many parts of the world, such as the Baltic and Adriatic Seas and the Gulf of Mexico (Hall 2002).

Nutrient management can be undermined by the loss of wetlands that assimilate nutrients and some pollutants

Nutrient management can be undermined by the loss of wetlands that assimilate nutrients (nitrogen, phosphorous, organic material) and some pollutants. Extensive evidence shows that up to 80% of the global incident nitrogen loading can be retained within wetlands (Green and others 2004; Galloway and others 2004). However, the ability of such ecosystems to cleanse nutrient-enriched water varies and is not unlimited (Alexander, Smith, and Schwarz 2000; Wollheim and others 2001). Verhoeven and others (2006) point out that many wetlands in agricultural catchments receive excessively high loadings of nutrients, with detrimental effects on biodiversity. Wetlands and lakes risk switching from a state in which they retain nutrients to one in which they release nutrients or emit

box 6.7 | **Regime shifts from excessive nutrient loads**

There are reported cases of regime shifts occurring in lakes because of increased nutrient loading, resulting in the loss of ecosystem services such as fisheries and tourism (Folke and others 2004). Some temperate lakes have experienced shifts between a turbid water and a clear water state, with the shift often attributed to an increase in phosphorous loading (Carpenter and others 2001). Some tropical lakes have shifted from a dominance of free-floating plants to submerged plants, with nutrient enrichment seemingly reducing the resilience of the submerged plants, possibly through shading and changes in underwater light (Scheffer and others 2001). Other wetlands and coastal habitats have also experienced similar shifts. In the United States nutrient enrichment caused a shift in emergent vegetation in the Everglades and a shift from clear water to murky water with algal blooms in Florida Bay (Gunderson 2001).

Other evidence comes from lakes subject to infilling and nutrient enrichment. In Lake Hornborga in Sweden emergent macrophytic vegetation proliferated after initial infilling of the lake margins and increased runoff of nutrients. The situation was reversed only after massive mechanical intervention and investment (Hertzman and Larsson 1999). In Australia agricultural runoff has resulted in shifts in vegetation dominance as a consequence of nutrient enrichment, increased inundation and salinization (Davis and others 2003; Strehlow and others 2005).

the greenhouse gas nitrous oxide. Regime shifts are often rapid, but they have likely followed a slower and difficult to detect change in ecosystem resilience. It is generally difficult to monitor changes in resilience before a system hits the threshold and changes from one state to another (box 6.7; Carpenter, Westley, and Turner 2005).

Agrochemical contamination. Pollution and contamination from agricultural chemicals have been well documented since the publication of the seminal book *Silent Spring* (Carson 1962). Bioaccumulation as a consequence of the wide use of agrochemicals has had dire outcomes for many species that reside in or feed predominantly in wetlands or lakes that have accumulated residues from pesticides *[well established]*. The decline in the breeding success of raptors was a turning point in developing awareness about the dangers of using pesticides (Carson 1962).

Water contamination by pesticides has increased rapidly since the 1970s despite increased regulation, especially in developed countries

An increasing amount of analytical and ecotoxicological data has become available for aquatic communities, and more recent research has also focused on risk assessments and the development of diagnostic tests that can guide management decisions about the use of such chemicals (van den Brink and others 2003). Taylor, Baird, and Soares (2002) have highlighted the high levels of pesticide use and low levels of environmental risk assessment in developing countries. They have promoted an integrated approach to evaluating environmental risks from pesticides that incorporates stakeholder consultation, chemical risk assessment, and ecotoxicological testing for ecological effects, also taking into account the potential effects on human health.

Vörösmarty, Lévêque, and Revenga (2005) report that water contamination by pesticides has increased rapidly since the 1970s despite increased regulation of the use of xenobiotic substances, especially in developed countries. However, bans on the use of these chemicals have generally been imposed only two to three decades after their first commercial use, as with DDT and atrazine. Many of these substances are highly persistent in the environment, but because of the generally poor monitoring of their long-term effects the global and long-term implications of their use cannot be fully assessed. Policy responses to contamination may lag far behind the event, as shown in the well documented case of agricultural pesticide bioaccumulation of DDT in the Zambezi Basin (Berg, Kilbus, and Kautsky 1992).

Siltation of rivers. In many parts of the world extensive sheet wash and gully erosion due to land management practices have devastated large areas, reduced the productivity of wide tracts of land, led to rapid siltation of reservoirs and threatened their longevity, and increased sediment loads in many rivers (see chapter 15 on land). On a regional scale some reservoirs in Southern Africa are at risk of losing more than a quarter of their storage capacity within 20–25 years (Magadza 1995). While many Australian and Southern African waters are naturally silty, many have experienced increased silt loads as a result of agricultural practices (Davies and Day 1998). Zimbabwe's more than 8,000 small to medium-size dams, for example, are threatened by sedimentation from soil erosion, while the Save River, an international river shared with Mozambique, has been reduced from a perennial to a seasonal river system due in large part to increased siltation as a result of soil erosion.

Globally, rivers discharge nearly 38,000 cubic kilometers of freshwater to the oceans and carry roughly 70% of the sediment input, though rivers draining only 10% of the land area contribute 60% of the total sediment discharge (Milliman 1991). The high sediment loads carried by Asian rivers are a consequence of land-use practices, particularly land-clearing practices for agriculture that lead to erosion, a situation likely to continue as a consequence of the expansion of agriculture in Africa, Asia, and Latin America (Hall 2002). A notable outcome of the supply of sediment and associated nutrients to the oceans is the increased frequency and intensity of anoxic conditions in recent years (Hall 2002).

There are also situations where river regulation has caused a decline in silt transport to downstream habitats, with reduced siltation along floodplains and in deltas and other downstream ecosystems. This has occurred in the Mesopotamian Marshes, where large-scale drainage is a bigger problem than silt-related changes in the downstream ecosystems (box 6.8).

Terrestrial ecosystems

Hydrological changes that occur as a result of agricultural expansion, particularly into forests, are seldom thought of in terms of water management in agriculture, although such changes are of at least the same magnitude as those resulting from irrigation (Gordon and others 2005). This is an area in need of further research, especially as biofuels and tree

box 6.8 | Desiccation of the Mesopotamian wetlands

The Mesopotamian wetlands, one of the cradles of civilization and a biodiversity center of global importance, used to cover more than 15,000 square kilometers in the lower Euphrates and Tigris Basins. Agricultural development and other drainage activities over the past 30 years have reduced them to 14% of their original size, and vast areas have been turned into bare land and salt crusts (Richardson and others 2005). The ecological implications have been severe, with drastic land degradation and impacts on wildlife, including bird migration and the extinction of endemic species, and on the ecology of the downstream Shatt el Arab and coastal fisheries in the Persian Gulf. The local population of half a million Marsh Arabs have become environmental refugees.

The causes of this severe ecological degradation are complex. Some of the causes were intentional, the results of drainage efforts to reclaim marshland, deal with soil salinization, improve agricultural productivity, and strengthen military security in southern Iraq in the 1980s and 1990s. Other causes were unintentional and included both the large-scale consumptive water use in irrigation systems and the return of saline drainage, agricultural and industrial chemical pollution, and the loss of flood flow, with its load of silt and nutrients, linked to recent large-scale streamflow regulation in upstream Turkey.

With the extent of existing regulation and degradation, the proposed rehabilitation of 30% of the Central Marshes upstream of the confluence of the Euphrates and Tigris could generate its own adverse impacts on aquatic ecosystems further downstream. The additional evaporation from just 1,000 square kilometers of restored open-water surfaces would consume an average flow of 67 cubic meters per second, or 25% of the original (pre-regulation) dry season flow, and reduce downstream streamflow even further. Without an increase in the amount of water available, simply returning the water to upstream areas may not be enough to restore the marshes and could further reduce the flow of water to downstream areas.

Source: Partow 2001; Italy, Ministry for the Environment and Territory, and Free Iraq Foundation 2004.

plantations for carbon sequestration are new driving forces in the agricultural sector with potentially major, but largely unassessed, consequences for water use (Jackson and others 2005; Berndes 2002). Forest clearing for agriculture has hydrological consequences *[well established]*, but site-specific responses will vary. Deforestation can lead to land degradation through salinization, soil loss, and waterlogging (for discussion on irrigation-induced salinity, see chapter 15 on land).

There is increasing speculation about how altered green water flows affect local, regional, and global climate. Most of the evidence comes from tropical semiarid to humid climates, with little from temperate regions. This section reviews the evidence of water-related changes in terrestrial ecosystems as a response to agriculture.

Decreased infiltration of water into the soil, often a result of poor management of crop and grazing land, can cause desiccation of the soil

Changes in the water table. Water can build up in the soil profile if the rate of input, through irrigation, for example, exceeds the rate of throughput (for example, crop water consumption). This can cause water logging and salinization, which are extensively described for irrigated agriculture (Postel 1999). Continuous irrigation can result in soil salinization. Tanzania has an estimated 1.7–2.9 million hectares of saline soils and 300,000–700,000 hectares of sodic soils (FAO and UNESCO 2003), some of it now abandoned. Salt-affected soils in irrigation schemes are often related to poor soil and water management in addition to the unsuitability of many soils for irrigation (see chapters 9 on irrigation and 15 on land).

Clearing woody vegetation for pastures and crops can also lead to dryland salinization. Tree-covered landscape can provide an important regulating service by consuming rainfall by high evapotranspiration, limiting groundwater recharge, and keeping the groundwater low enough to prevent salt from being carried upward through the soil. Australia has had major problems with soil salinization since native woody vegetation was cleared in the 1930s for pastures and agricultural expansion (Farrington and Salama 1996). Consumptive water use has declined, the water table has risen, and salt has moved into the surface soils so that large tracts of land have become less suitable—and even unusable—for agriculture (Anderies and others 2001; Briggs and Taws 2003). Green water flows at a continental scale have been reduced by 10% (Gordon, Dunlop, and Foran 2003).

Decreased infiltration of water into the soil, often as a result of poor management of crop and grazing land, is another problem that can cause changes in the water table with effects on terrestrial systems, including a reduction in the capacity to produce biomass (Falkenmark and Rockström 1993). This is a well-known problem in many rainfed farming systems (see chapters 8 on rainfed agriculture and 15 on land). Desiccation of the soil in this manner is one of the factors behind what is often referred to as "desertification" or land degradation in the tropics.

Changes in runoff from vegetation change. The effects of alterations to vegetation (especially forests) on blue and green water flows are well studied at a local and regional scale. Catchment-scale experiments have shown that forested catchments in general have a higher green water flow and a lower blue water flow than grass or crop-dominated catchments with the same hydrology and climate. However, the effects of deforestation depend on the intensity and manner of forest clearance and on the character of the old and new land cover and its management (McCulloch and Robinson 1993; Bosch and Hewlett 1982; Bruijnzeel 1990).

General work on the influence of vegetation, climate, and land cover on the water balance of a system has shown that there are vegetation-specific changes (L'vovich 1979; Calder 2005). Management of plant production that redirects blue water to green water can reduce the amount of water to downstream systems (Falkenmark 1999). For example, replacing crop or grasslands with forest plantations can decrease runoff and streamflow (Jewitt 2002). The South African Water Act classifies forest plantations as a "streamflow reduction activity," and forestry companies have to pay for their water use since less of the precipitation reaches the river.

There are indications that increased vapor flows through irrigation can alter local and regional climates

Moisture recycling. Clearing land for agriculture and increasing use of irrigation have modified green water flows globally, reducing them by 3,000 cubic kilometers through forest clearing and increasing them by 1,000–2,600 cubic kilometers in irrigated areas (Döll and Siebert 2002; Gordon and others 2005). The ability of changes in land cover to influence climate through changes in green water flow has been increasingly recognized. It has been suggested that large-scale deforestation can reduce moisture recycling, affect precipitation (Savenije 1995, 1996; Trenberth 1999), and alter regional climate, with indications of global impacts (Kabat and others 2004; Nemani and others 1996; Marland and others 2003; Savenije 1995).

Pielke and others (1998) conclude that the evidence is convincing that land cover changes can significantly influence weather and climate and are as important as other human-induced changes for the Earth's climate. However, the models employed do not deal explicitly with green water flows, but rather with the compounded effects of changes in albedo, surface wind, leaf area index, and other indicators. Nevertheless, regional studies in West Africa (Savenije 1996; Zheng and Eltathir 1998), the United States (Baron and others 1998; Pielke and others 1999), and East Asia (Fu 2003) have illustrated that changes in land cover affect green water flows, with impacts on local and regional climates. Likewise, biome-specific models of land cover conversions from rainforest to grasslands have shown a decrease in vapor flows and precipitation as well as effects on circulation patterns (Salati and Nobre 1991) and savannahs (Hoffman and Jackson 2000). There are also indications that increased vapor flows through irrigation can alter local and regional climates (Pielke and others 1997; Chase and others 1999). The conversion of steppe to irrigated croplands in Colorado resulted in a 120% increase in vapor flows (Baron and others 1998), contributing to higher precipitation, lower temperatures, and an increase in thunderstorm activity (Pielke and others 1997).

Whether these changes can trigger rapid regime shifts (box 6.9), which in many cases may be irreversible, and changes to which farmers need to adapt is still speculative. In the Amazon the clearing of land has reduced moisture recycling, resulting in prolonged dry seasons and increased burning, and may have triggered an irreversible regime shift from rainforest vegetation to savannah (Oyama and Nobre 2003). There is also increasing concern about changes in the African and Asian monsoons, including weakening of the East Asian summer monsoon low-pressure system and an increase in irregular northerly flows (Fu 2003). Likewise, modeled vegetation changes for agricultural expansion in West Africa have shown potentially dramatic impacts on rainfall in the African monsoon circulation (Zheng and Eltathir 1998).

box 6.9 **Resilience and the increased risk of rapid regime shifts in ecosystems**

Ecosystems change and evolve, with disturbance now seen as an inherent component of ecosystem processes *[well established]*. The speed of change in many ecosystems has, however, increased rapidly, and there is now concern that large-scale changes will increase the vulnerability of some ecosystems to water-related agricultural activities. Ecosystems are complex adaptive systems (Levin 1999), with nonlinear dynamics and thresholds between different "stable states." Nonlinear changes are sometimes abrupt and large, and they may be difficult, expensive, or impossible to reverse. The increased likelihood of nonlinear changes stems from drivers of ecosystem change that adversely affect the resilience of an ecosystem, its capacity to absorb disturbance, undergo change, and still retain essentially the same function, structure, identity, and feedbacks (Gunderson and Holling 2002; Carpenter and others 2001) and provide components for renewal and reorganization (Gunderson and Holling 2002).

Variability and flexibility are needed to maintain ecosystem resilience. Attempts to stabilize systems in some perceived optimal state, whether for conservation or production, have often reduced long-term resilience, making the system more vulnerable to change (Holling and Meffe 1996). While today's agricultural systems are able to better deal with local and small-scale variability, the simplifications of landscapes and reduction of other ecosystem services have decreased the capacity of agricultural systems and other ecosystems to cope with larger scale and more complex dynamics through reduced ecosystem resilience locally and across scales (Gunderson and Holling 2002).

Little is yet known about how to estimate resilience and detect thresholds before regime shifts occur (Fernandez and others 2002). Better mechanisms to monitor regime shifts include the identification and monitoring of slowly changing variables (Carpenter and Turner 2000) and measurable "surrogates of resilience" (Bennett, Cumming, and Peterson 2005; Cumming and others 2005).

Societal responses and opportunities

The negative effects of past agricultural management on ecosystem services and the need to produce more food for growing populations provide an unparalleled challenge. Meeting this challenge requires large-scale investments to improve agricultural management practices, increase the availability of techniques to minimize adverse ecological impacts, enhance our understanding of ecosystem-agriculture interactions, and reduce poverty and social inequities, including issues of gender, health, and education that affect ecosystem management decisions.

In presenting possible responses for meeting this challenge, we emphasize several ecological outcomes that we consider to be critical in this effort: maintenance or rehabilitation of the ecological connectivity, heterogeneity, and resilience in the landscape, which in turn implies maintenance or rehabilitation of the biodiversity that characterizes the landscape. We focus on integration and awareness of the negative consequences of choices in terms of the tradeoffs between food production and other ecosystem services. We do not propose specific responses for specific ecosystems or locations, although we aim to help national and local decisionmaking with a framework for addressing some of these issues. Many of the responses outlined are dependent on effective governance measures and policies that support sustainable development with a balance of ecological and social outcomes, issues covered in detail in chapters 5 on policies and institutions and 16 on river basins.

Improving agricultural technology and management practices

The Millennium Ecosystem Assessment (MEA 2005c) supports the view that intensification of agricultural systems will create fewer tradeoffs with ecosystem services than will expansion. Intensification will require improvements in agricultural productivity, especially in water productivity (see chapter 7 on water productivity) in water-scarce environments. However, because intensification can bring its own ecological problems, for example, through pollution or the introduction of invasive species, command and control approaches to management should be avoided (Holling and Meffe 1996). The potential problems of intensification could be lessened or avoided through the adoption of a systems approach to agriculture and integrated approaches to landscape management (see below).

> The potential problems of intensification could be lessened through the adoption of a systems approach to agriculture and integrated approaches to landscape management

Many of the chapters in this volume address agricultural techniques and improved management practices. Chapters 14 on rice and 15 on land highlight the need to consider techniques and practices that may not increase the production of one or a few specific crops but that support the provision of multiple benefits. Unless responses that restrict the potential adverse impacts of intensification are applied, intensification will not be any more environmentally and socially benign than many past agricultural practices.

Applying integrated approaches to water, agriculture, and other ecosystems

Integrated policy and management approaches are increasingly seen as crucial in facilitating decisionmaking and making tradeoffs between food and other ecosystem services. Integrated approaches have taken many forms, including integrated river basin management,

Photo by C. Max Finlayson

Photo 6.5 This use of wetlands in Malawi attempts to integrate multiple benefits and costs integrated land and water management, ecosystem approaches, integrated coastal zone management, and integrated natural resources management. Their general aim is often the same. They actively seek to address integration of all the benefits and costs associated with land-use and water decisions, including effects on ecosystem services, food production, and social equity, in a transparent manner; to involve key stakeholders and cross-institutional levels; and to cross relevant biophysical scales, addressing interconnectedness across subbasin, river basin, and landscape scales (photo 6.5).

While integrated approaches for environmental management are seen as an important effort and have long been promoted, there are few successful examples. The governance systems required to support the appropriate institutional and managerial arrangements, particularly for the allocation of resources and planning authority concomitant with responsibility at a local level, seem difficult to achieve (see, for example, chapter 16 on river basins). One complaint is that most of these approaches are based on a technocratic view of decisionmaking, whereas real life is far messier, with power struggles, lack of trust between and within stakeholder groups, and complex and evolutionary behavior of ecosystems that make it difficult to assess total benefits and impacts. Folke and others (2005) see a need for more emphasis on building, managing, and maintaining collaborative social relationships for river basin governance, which is in line with current thinking about ecosystem management.

While integrated approaches for environmental management have long been promoted, there are few successful examples

Where river basin organizations have succeeded, that has often been because of their ability to deliver on the common aims of jurisdictions (such as coordinated water management to supply irrigation). The situation is more complex when dealing with international transboundary rivers, such as the Nile and the Mekong. An alternative to river basin processes may be to explore more regional guidance for common policies, as is being developed in Southern Africa (box 6.10).

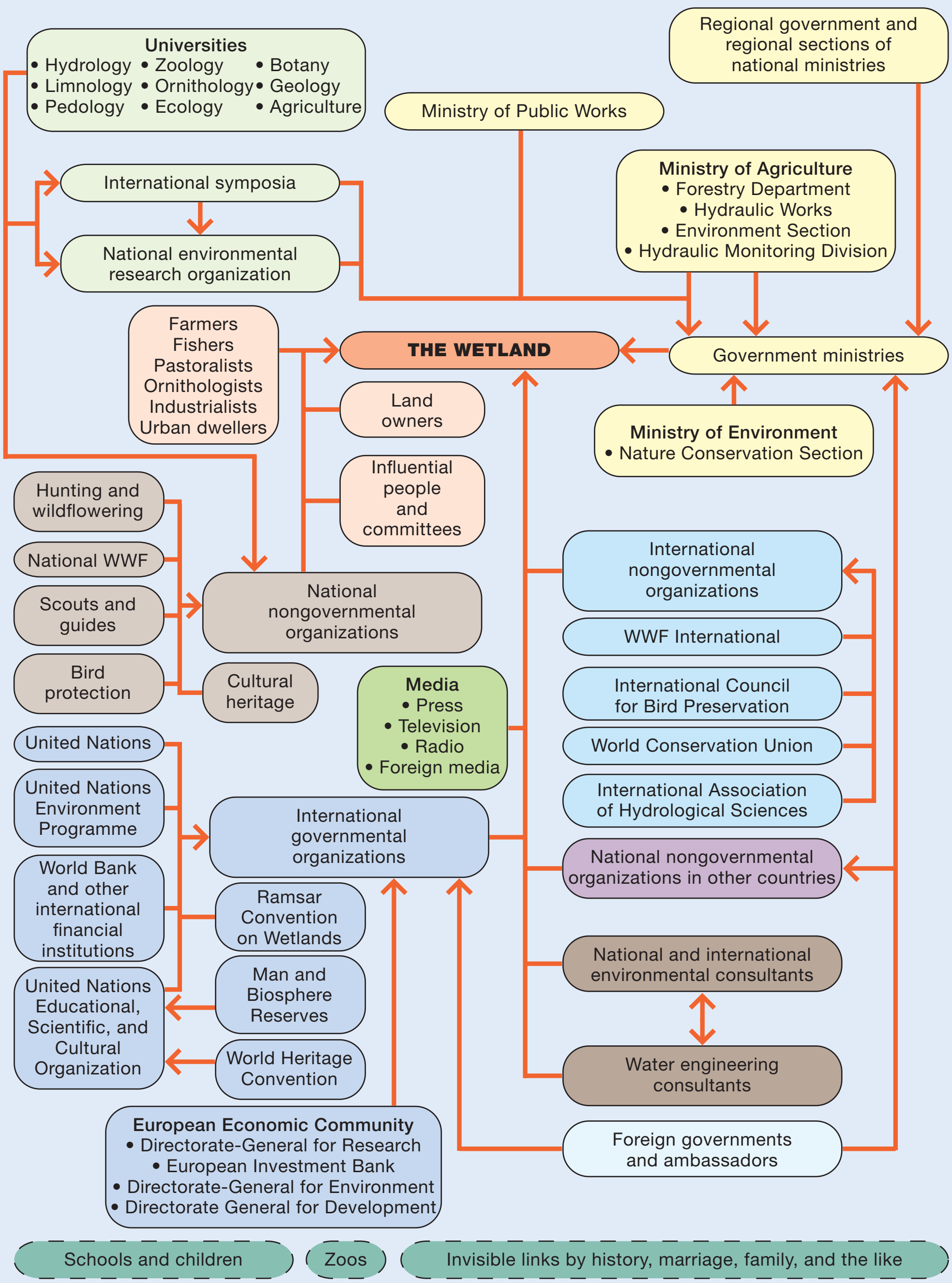
The complexity of the social policy and institutional links that govern ecosystem management and influence necessary tradeoffs is shown for wetlands in figure 6.3. Differences in local contexts may affect the manner in which relationships between individuals

box 6.10 | National and regional policy initiatives on water and ecosystems

The South African National Water Act of 1998 protects the water requirements for ecosystems and supports them through an ongoing scientific effort. This is in line with the principles contained in the Southern African Development Commission (SADC) regional water policy of May 2004, which recognizes the environment as a legitimate user of water and calls on SADC members to adopt all necessary strategies and actions to sustain the environment. At the national level water reforms in South Africa and Zimbabwe have successfully mainstreamed environmental water requirements in water resources policy and legislation. Namibia is similarly considering policy that stresses sectoral coordination, integrated planning and management, and resource management aimed at coping with ecological and associated environmental risks.

Mexico's 1992 Law of National Waters is another example of national water reforms that consider ecosystem needs. It empowers the federal government to declare as disaster areas watersheds or hydrological regions that represent or may represent irreversible risks to an ecosystem.

figure 6.3 **The complexity of the social policy and institutional linkages that govern ecosystem management and influence necessary tradeoffs in wetlands**



Source: Hollis 1994.

and institutions are built and maintained. High levels of knowledge and human capacity are considered critical to crafting the institutions and policies required for successful integrated water management (see chapter 5 on policies and institutions). This chapter emphasizes the need to raise awareness of the role of ecosystem services in societal well-being in both multifunctional agricultural systems and across landscapes and on the importance of maintaining the ecological and social processes that support these.

Assessing and nurturing multiple benefits

Improving awareness and understanding. Integrated approaches help to deal with the competing interests in water resources They make it possible to share the multiple benefits and costs that are generated across a river basin and that are improved or degraded through agricultural interventions in the landscape.

Assessment of the multiple ecosystem services and the processes that support them is a key component of these approaches. Historically, decisions concerning ecosystem management have tended to favor either conversion of ecosystems or management for a single ecosystem service, such as water supply or food production, often without consideration of the effects on such groups as the rural poor, women, and children (MEA 2005c). Many ecosystem services do not have a price on the market and are often neglected in policymaking and decisionmaking. As we better understand the benefits provided by the entire array of ecosystem services, we also realize that some of the best response options will involve managing landscapes, including agriculture, for a broader array of services. That will entail taking greater account of social issues, such as gender-based roles and poverty, when making decisions about agriculture and water management (WRI and others 2005).

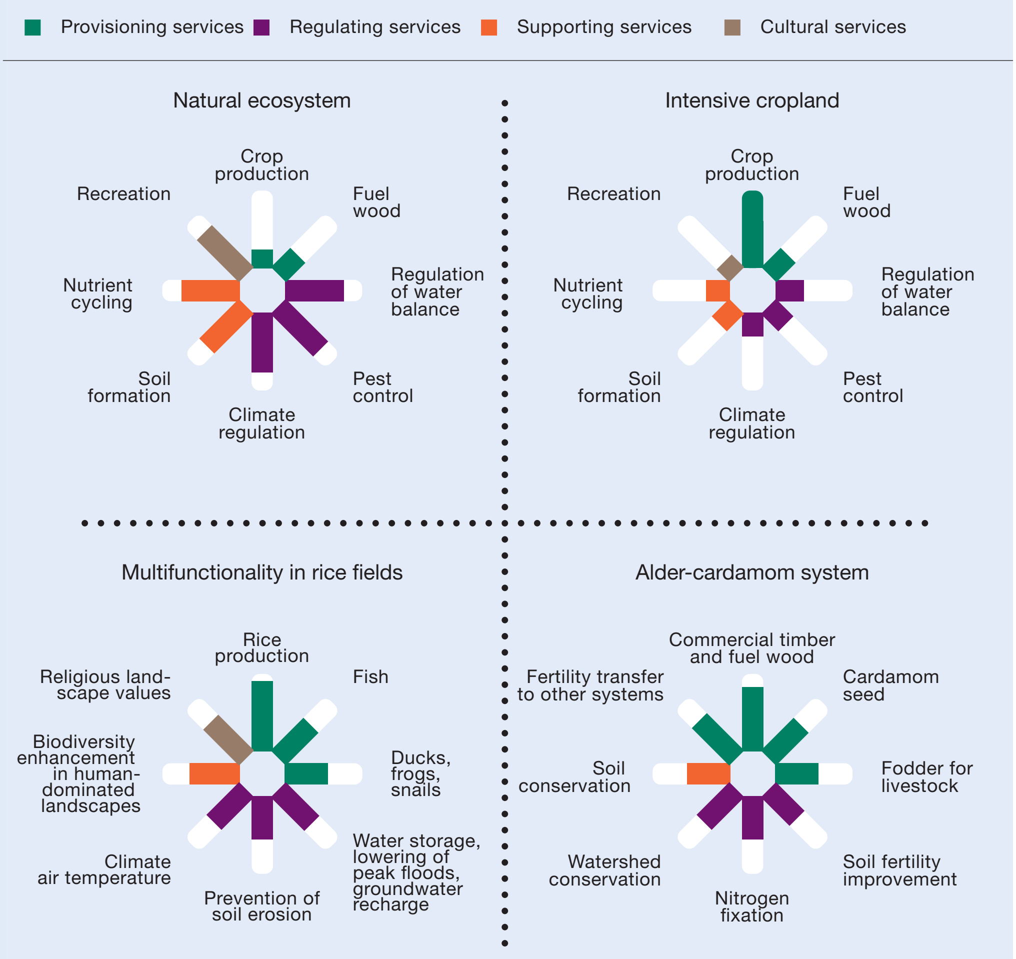
> Historically, decisions concerning ecosystem management have tended to favor conversion of ecosystems or management for a single ecosystem service, such as food production

The Millennium Ecosystem Assessment has provided a major advance in understanding the links between the provision of ecosystem services and human well-being (www.maweb.org). Increased awareness is still needed on several different levels. The scientific knowledge of how ecosystem services contribute to human well-being within and between different sectors of society, and the role of water in sustaining these services, need to be improved. Dissemination of information on these issues and dialogue with stakeholders should be enhanced. Civil society organizations can help to ensure that appropriate consideration is given to the voices of individuals and social groups and to nonutilitarian values in decisionmaking. Minority groups and disadvantaged groups, such as indigenous people and women, in particular, need to be heard. Women play a critical and increasing role in agriculture in many parts of the developing world (Elder and Schmidt 2004).

Urbanization provides new challenges. For the first time in human history more people live in cities than in the rural areas. It has been estimated that the urban areas in the Baltic Sea region in northern Europe need an area of functioning ecosystems some 500 times the size of the cities themselves to generate the ecosystem services they depend on (Folke and others 1997). The green water needs for ecosystem services that support these cities are roughly 54 times larger than the blue water needs of households and industry (Jansson and others 1999). However, people who live in cities often become mentally disconnected from the ecological and hydrological processes that sustain their well-being. In this perspective farmers are the stewards of the landscape in which cities lie. This provides a new challenge for water and ecosystem management.

One of the main gaps in our scientific understanding of ecosystems and ecosystem services is where the thresholds lie and how far a system can be changed before it loses too many essential functions and totally changes its behavior (Gunderson and Holling 2002). Without this knowledge the early warning indicators required to provide advance warning of anticipated adverse change or of when a threshold is being approached cannot be developed.

figure **6.4** **Comparison of intensive agricultural systems managed for the generation of one ecosystem service and multifunctionality in agroecosystems**



Source: Adapted from Foley and others 2005; chapters 14 and 15 in this volume.

Managing agriculture for multiple outputs. Increasing attention to ecosystem services provides an opportunity to emphasize multifunctionality within agroecosystems and the connectivity between and within agroecosystems and other ecosystems. It is often assumed that agricultural systems are managed only for optimal (or maximum) production of one ecosystem service, food, or fiber (figure 6.4). But agricultural systems can generate other ecosystem services, and we need to improve our capacity to assess, quantify, and value these as well. Encouraging multiple benefits from these systems can generate synergies that result in the wider distribution of benefits across more people and sectors. Ecosystem-based approaches to water management need not constrain agricultural development but can be points of convergence for social equity, poverty reduction, resource conservation, and international concerns for global food security, biodiversity conservation, and carbon sequestration (see chapter 15 on land). Ecosystem-based approaches aim to maintain and where possible enhance diversity and to build the ecological resilience of the agricultural landscape as well as of ecosystems altered by agriculture (box 6.11).

The concept of multifunctional agriculture is not new; it has long been practiced in many forms and combinations. Integrated pest management is one way to manage a whole landscape in order to sustain an ecosystem service (pest control) that enhances agricultural production. This type of regional management requires integrated approaches based on an ecological understanding of fragmentation and landscape heterogeneity (Cumming and Spiesman 2006). Hydrological understanding is also important. Studies have shown that it is possible to control insect outbreaks by timing irrigation events (Lansing 1991) and that

box 6.11 | Some basic principles for maintaining ecosystem resilience

The resilience perspective shifts from policies that aspire to control change in systems assumed to be stable to policies to manage the capacity of social-ecological systems to cope with, adapt to, and shape change (Berkes, Colding, and Folke 2003). Managing for resilience enhances the likelihood of sustaining development in changing environments where the future is unpredictable.

Variability, disturbance, and change are important components of an ecosystem. For example, when variability in river flows is altered, marked changes in ecosystem functions can be expected (Richter and others 2003). Wetting and drying of soils can be important for the resilience of ecosystem functions, such as pest control and nutrient retention in wetlands. Exactly what level of variability to maintain and when variability is site specific are areas of intense research (Richter and others 2003). Maintaining diversity has been shown to be important for building ecosystem resilience, in particular for maintaining functional and response diversity (Elmqvist and others 2003; MEA 2005c). Responses should therefore seek to maintain and enhance diversity in ecosystems and across broader landscapes while maintaining food production.

The driving variables behind the functioning of ecosystems tend to have slower dynamics than those that support the ecosystem services generated from that system (Carpenter and Turner 2000). Therefore, the monitoring of long-term ecosystem performance should cover the productivity of the ecosystem and the crucial variables that enable production. This is particularly evident when monitoring the productivity of croplands. Harvested yields are an important measure, but they may not tell the full story. Long-term productivity likely depends on slower variables, such as the accumulation and decomposition of soil organic matter.

planting trees in particular parts of the landscape can reduce vulnerability to waterlogging and salinization in other parts of the landscape (Andreis 2005).

Other chapters in this volume propose multifunctional agriculture as a response to the environmental degradation resulting from more narrowly based agricultural practices. For example, chapter 14 on rice illustrates the different ecosystem services generated in rice fields. Chapter 8 on rainfed agriculture illustrates how modifications to the water balance and erosion control can increase crop production. And chapter 9 on irrigation emphasizes multifunctionality in large-scale public irrigation systems that are dependent on surface water. Chapter 15 on land also presents a comprehensive overview of multifunctional agriculture and landscapes, including resource-conserving agriculture and emphasizes the synergies that arise between multiple users of ecosystem services when agriculture is treated as an integral part of the broader landscape. These chapters also illustrate the close links between environmental change and well-being and highlight the different roles and responsibilities of women and men in agriculture, the economy, and the household, and their different effects on the environment, issues requiring further study.

Given past failures to secure the wider range of ecosystem services, we highlight the need for tools that can be used in striking tradeoffs between water for different ecosystem services

Assessing tradeoffs and tools for dealing with them

Scientists are increasingly questioning the wisdom of seeking economic development, including further development of agriculture and fisheries, at the expense of wider environmental and social consequences (International Council for Science 2002; SIWI and others 2005; Foley and others 2005; Kura and others 2004). Arrow and others (1995) have shown convincingly that economic development without due consideration of the ecological consequences may not provide the economic means to overcome environmental concerns in the future, particularly if the ecological resilience of the wider environment is undermined. The consequences of losing ecological resilience, especially when it results in irreversible change, have not been fully considered alongside the expected benefits (MEA 2005c).

It is anticipated that the management of water for agroecosystems alone will be subject to competition from wider environmental requirements (Lemly, Kingsford, and Thompson 2000; Molden and de Fraiture 2004) and may require further tradeoffs and the adoption of wider and more inclusive mechanisms. For example, the public sector is starting to buy back irrigation water from farmers to sustain or rehabilitate ecosystems or ecosystem services, sometimes even paying farmers not to irrigate. Governments may be able to buy the rights to water (whether the rights had previously been given away or obtained through the market), or nongovernmental organizations may be able to lease the water during dry years to support valued aquatic ecosystems. Water for the environment can thus be seen as a new driving force to which agriculture needs to adapt.

Ecosystem management is increasingly undertaken through collaborative planning and consultation processes, following past failures to transparently consider tradeoffs and wider societal interests (Carbonell, Nathai-Gyan, and Finlayson 2001). The Millennium Ecosystem Assessment (MEA 2005b,c) emphasizes the importance of overcoming sectoral divides and encompassing wider stakeholder participation in planning and development. Some of the people most vulnerable to ecosystem change depend directly on ecosystem services for their livelihoods, and they have often lacked a voice in making decisions about these services (Carbonell, Nathai-Gyan, and Finlayson 2001). Many local people who depend on ecosystems have had to develop management practices to deal with disturbances and change in a way that builds socioecological resilience (Berkes and Folke 1998). They can contribute their understanding of fundamental ecosystem processes (Olsson, Folke, and Hahn 2004). For the social mechanisms of dealing with the conflicts that occur when making tradeoffs see chapter 5 on policies and institutions and chapter 16 on river basins.

New tools are emerging for dealing with tradeoffs, including some that provide economic incentives and support the formulation of policies and regulations. Given past failures to secure the wider range of ecosystem services, we highlight the need for developing and adopting tools that can be used in striking tradeoffs between water for different ecosystem services. Such tools include economic valuation and cost-benefit analysis of ecosystem services, assessment of environmental flows, risk and vulnerability assessments, strategic and environmental impact assessments, and probability-based modeling.

A wide range of methods are available for valuing ecosystems beyond the use of direct market prices

Successful employment of such tools requires an adequate information base and improved predictive capacity about how ecosystems respond to change, and articulation of what is unknown or uncertain (Carpenter and others 2001). While the use of such tools has been increasingly promoted through international forums, conventions, and treaties, lack of awareness and capacity still seems to impede their use. We focus here on two tools that have considerable potential to assist in making tradeoffs: economic valuation of ecosystem services and allocation of environmental flows.

Ecosystem valuation. Economic valuation is a powerful tool for addressing the tradeoffs between food production and other ecosystem services when making decisions about water management in agriculture. Its broad aim is to quantify the benefits (both market and nonmarket) that people obtain from ecosystem services to enable decisionmakers and the

box 6.12 | The total economic value of ecosystems

Total economic value involves assessing the value of four categories of ecosystem services:

- *Direct use values* are derived from ecosystem services that are used directly by people and include the value of consumptive uses, such as the harvesting of food products, timber, medicinal products, and the hunting of animals, as well as the value of nonconsumptive uses, such as the enjoyment of recreational and cultural amenities, water sports, and spiritual and social services.
- *Indirect use values* are derived from ecosystem services that provide benefits outside the ecosystem itself, for example, the water filtration function of wetlands, the storm protection function of mangrove forests and delta islands, and carbon sequestration by forests.
- *Option values* are derived from preserving the option to use services in the future rather than now, either by oneself (option value) or by heirs or others (bequest value).
- *Nonuse* (or existence) *values* refer to the value people may place on knowing that a resource exists even if they never use that resource directly.

Source: MEA 2005b.

public to evaluate the economic costs and benefits of any proposed change in an ecosystem and to facilitate comparison with other aspects of the economy. Economic valuation is just one way of assessing tradeoffs. It is especially useful in the context of economic arguments favoring actions leading to ecosystem degradation that fail to take full account of the economic costs. Ecosystem valuation assists in the efficient allocation of resources, enhances the scope for market creation, and can reduce the magnitude of market failures.

Total economic value (box 6.12) has become a widely used framework for identifying and quantifying ecosystem services (Balmford and others 2002; MEA 2005c). It considers the full range of ecosystem characteristics together—resource stocks or assets, flows of environmental services, and attributes of the ecosystem as a whole. It covers direct and indirect values and option and nonuse values.

box **6.13** | **Commonly used valuation tools**

A wide array of methods can be used for economic valuation of ecosystems. Some of the most common are:

- *Replacement costs*. Even where ecosystem services have no market value themselves, they often have alternatives or substitutes that can be bought and sold. These replacement costs can be used as a proxy for ecosystem resources, although they usually represent only partial estimates or are underestimates.
- *Effects on production*. Other economic processes often rely on ecosystem resources as inputs or on the essential life support provided by these services. Where they have a market, it is possible to look at the contribution of the services to the output or income of these wider production and consumption opportunities in order to assess their value.
- *Damage costs avoided*. The reduction or loss of ecosystem services frequently incurs costs in terms of damage to or reduction of other economic activities. The damage costs that are avoided can be taken to represent the economic losses forgone by conserving ecosystems.
- *Mitigative or avertive expenditures*. It is almost always necessary to take action to mitigate or avert the negative effects of the loss of ecosystem services so as to avoid economic damage. These costs can be used as indicators of the value of conserving ecosystems in terms of expenditures avoided.
- *Hedonic pricing*. Hedonic methods look at the differentials in property prices and wages between locations and isolate the proportion of this difference that can be ascribed to the existence or quality of ecosystem services.
- *Travel costs*. Many ecosystems typically hold a high value as a recreational resource or destination. Although in many cases no charge is made to view or enjoy less human-dominated ecosystems, people must still spend time and money to reach them. This expenditure—on transport, food, equipment, accommodations, time, and so on—can be calculated, and a demand function can be constructed relating visitation rates to expenditures made. These travel costs reflect the value that people place on the leisure, recreational, or tourism aspects of specified ecosystems.
- *Contingent valuation*. Even where ecosystem services have no market price and no close replacements or substitutes, they frequently have a high value to people. Contingent valuation techniques infer the value that people place on these services by asking about willingness to pay for them (or willingness to accept compensation for their loss) under the hypothetical scenario that they would be available for purchase.

A wide range of methods are available for valuing ecosystems beyond the use of direct market prices. These include approaches that elicit preferences directly (such as contingent valuation methods) and those that use indirect methods to infer preferences from actions to purchase related services (for example, through production functions, dose-response relationships, travel costs, replacement costs, and mitigative expenditures). These methods are summarized in box 6.13.

While economic tools may prove useful in striking tradeoffs, they are unlikely to be useful in all circumstances. The more sophisticated the method, the less useful it is likely to be in situations where data are not available or where political issues hold sway. Economic tools can assist in understanding only the economic tradeoffs, not the political tradeoffs or the role of complex social relationships such as the role of gender and culture.

Tools have been developed to assist in making decisions for allocating water for both economic and environmental purposes

In the last two decades the notion of paying for ecosystem services has begun to emerge (WWF 2006). Such projects typically involve local land and water managers (including farmers) and use financial initiatives to encourage management changes that increase ecosystem services. The idea behind the initiatives is that beneficiaries of the service should compensate those who "provide" the environmental services by conserving natural ecosystems. Some of the better known projects concern watershed restoration (decreased erosion, decreased nutrient runoff).

Environmental water flows. Environmental flows refer to the quantity, seasonality, and quality of water considered to be sufficient for protecting the structure and function of an ecosystem and its dependent species and services, taking into account temporal differences in water requirements and spatial variability. The allocation of an environmental flow is defined by the long-term availability of water, including the extent of natural and anthropogenic temporal and spatial variability and identified ecosystem responses (Dyson, Bergkamp, and Scanlon 2003). Environmental flows are often established through environmental, social, and economic assessments (King, Tharme, and Sabet 2000; Dyson, Bergkamp, and Scanlon 2003). Determining how much water can be allocated to consumptive human uses without the loss of ecosystem services is becoming a more common component of efforts to maintain and rehabilitate rivers and wetlands, including estuaries and other coastal ecosystems.

To date, most developing countries with significant irrigation have paid relatively little attention to safeguarding flows for the environment (Tharme 2003), but this situation is expected to change rapidly in the coming decades. Water legislation in South Africa and the Mekong Agreement are examples of the recognition of environmental water requirements in developing countries. More explicit bulk allocation of water to the environment may provide a major challenge to irrigators to manage with smaller and less dependable allocations for cropping. While the assessment of water availability, water use, and water stress at the global scale has been the subject of ongoing research, the water requirements of aquatic ecosystems have not been considered explicitly or estimated globally (Smakhtin, Revenga, and Döll 2004). It could be possible to establish an environmental allocation beyond which substantial degradation of ecosystem services and human well-being results (King, Tharme, and Sabet 2000). Defining this allocation entails also defining what constitutes a degraded ecosystem.

Poff and others (1997) emphasize that analysis of environmental flows should consider both the quantity and the timing of flows to maintain "naturally variable flow regimes" with the aim of retaining the benefits provided by seasonally low and high flows. Several methods have been used to establish environmental flow allocations and to reduce or remediate problems caused by previous water regulation. King, Brown, and Sabet (2003) emphasize that monitoring and management adjustments are a necessary component of such methods. There are many methods for estimating the amount of water that is critical for preserving aquatic ecosystems and resources (Annear and others 2002).

> Most of the tools for dealing with tradeoffs involving ecosystem services work best in environments where ecosystem behavior is well understood, but mechanisms are needed for dealing with uncertainty

In addition to determining the suitable quantity and timing of an environmental flow, it may be necessary to consider how to deliver flows. The engineering structures along rivers can constrain flow releases and may need adjustment. The rate and volume of releases and the temperature and oxygen content of the water are all important components of a flow release. Tools have been developed to assist in making decisions for allocating water for both economic and environmental purposes. The Downstream Response to Imposed Flow Transformation framework (box 6.14) differs from others such as the Instream Flow Incremental Methodology and Catchment Abstraction Management Strategies in its explicit consideration of the socioeconomic implications of different release scenarios.

Conceptualizing uncertainty

Most of the tools that have been developed for dealing with tradeoffs involving ecosystem services work best in environments where ecosystem behavior and response to change are well understood and the problems and benefits are already known. But ecosystem

box 6.14 | Guiding environmental flows: the Downstream Response to Imposed Flow Transformation framework

The Downstream Response to Imposed Flow Transformation (DRIFT) framework is an interactive and holistic approach for providing advice on environmental flows in rivers. It incorporates knowledge from experienced scientists from a range of biophysical disciplines as well as socioeconomic information to establish flow-related scenarios that describe a modified flow regime, the resulting condition of the river or species, the effect on water resource availability for off-stream users, and the social and economic costs and benefits. DRIFT highlights the importance of maintaining groundwater ecosystems along with surface water ecosystems in securing streamflows for ecosystem purposes. The process is developed through interactive and multidisciplinary stakeholder workshops to develop agreed biophysical and socioeconomic scenarios.

The development of scenarios requires an assessment of biophysical, social, and economic data and draws on results from other predictive models that assess the responses of specific biota to flow conditions (such as the Physical Habitat Simulation model). To be effective DRIFT should be run in parallel with a macroeconomic assessment of the wider implications of each scenario and in conjunction with a public participation process that enables people other than direct users to contribute to finding the best solution for the river.

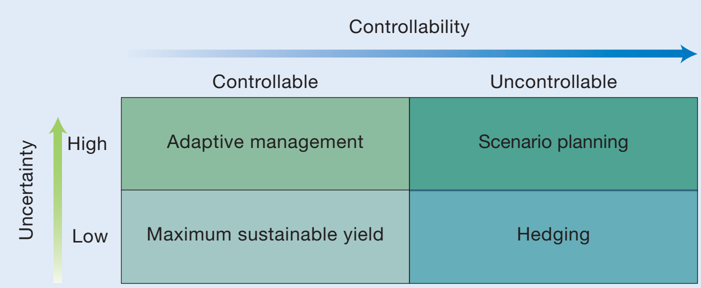
Source: Acreman and King 2003; MEA 2005b.

complexity and variability are common, so uncertainty is high, resulting in outcomes that are unpredictable and difficult to control. Mechanisms are needed for dealing with uncertainty that enable proactive rather than reactive responses to change.

Two interrelated approaches, adaptive management and scenario planning (see chapter 3 on scenarios), have been suggested for dealing with unpredictability (figure 6.5). Adaptive management and scenario planning both examine alternative models of how the world might work and seek to develop policies that are robust to this uncertainty. What distinguishes them is that the models used in adaptive management build in management experiments. The approaches are complementary to the integrated approaches described above and can be used together.

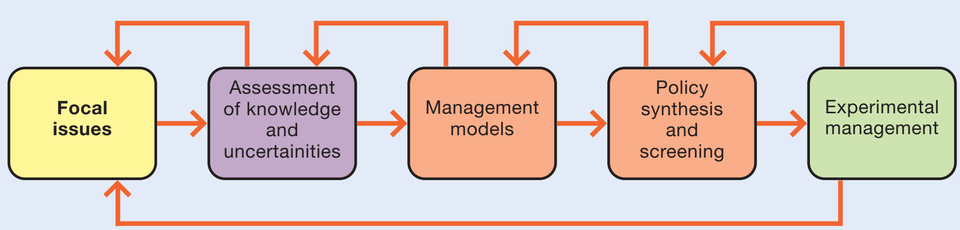
Adaptive management. Adaptive management emphasizes learning and flexibility in management institutions to cope with situations that involve unknown and uncertain ecological management tradeoffs (Walters 1986; Holling 1973; figure 6.6). Treating management policies as hypotheses rather than solutions, adaptive management has been a highly visible

figure **6.5** | **Different management approaches for dealing with uncertainty in information and the controllability of outcomes**



Source: Adapted from Peterson, Cumming, and Carpenter 2003.

figure **6.6** | **Adaptive management treats policy as hypothesis and management as experiments, emphasizing learning and evaluation of interventions**



policy instrument in the management of major river systems, including the Columbia (Lee 1993), Colorado (Walters and others 2000), San Pedro and the Apalachicola-Chattahoochee-Flint River (Richter and others 2003), and rivers in Kruger National Park (Rogers and Biggs 1999) and the Everglades (Walters, Gunderson, and Holling 1992). The key is identifying management-relevant uncertainties that underlie policies and then evaluating the management alternatives through scientific assessment, modeling, and if necessary, experimental management.

Successful adaptive management requires time, resources for learning, and social support (Richter and others 2003; Walters 1986). Consequently, it often focuses on building ecological resilience, establishing knowledge for ecological management by working to integrate knowledge from many different scientific and local sources, and developing connections between the system being managed and its larger context (Berkes, Colding, and Folke 2003).

Scenario planning offers a structured way of coping with complex systems and outcomes through learning and preparing for change

In an example of adaptive management Carpenter (2002) describes how a partnership of university researchers and state ecological managers collaborated to design and operate a management experiment to improve water quality in Lake Mendota, Wisconsin, by altering the fish community dynamics in the lake to increase predation of algae. The experiment was made possible by a history of collaboration between lake managers and academics and supported by the availability of decades of lake monitoring.

Scenario planning. Many problems related to management of water for agriculture and other ecosystem services are too complex and involve too many interest groups to be solved through narrowly focused experiments or computer model projections. Scenario planning offers a structured way of coping with complex systems and outcomes through learning and preparing for change (Peterson, Cumming, and Carpenter 2003; MEA 2005c). Decisions about how, when, and where to act are typically based on expectations for the future. When the world is highly unpredictable and when we are working from a limited range of experiences, our expectations may be proved wrong. Scenario planning provides a means to examine these expectations through a set of contrasting plausible futures described though a set of narratives. It has been applied in recent assessments such as the Intergovernmental Panel on Climate Change, the Millennium Ecosystem Assessment, and the International Assessment on Agricultural Science and Technology for Development.

Ideally, scenarios should build understanding of the potential costs and benefits of alternative futures. Scenario planning integrates diverse qualitative and quantitative information into a set of plausible narratives to explore policy-relevant futures. A scenario planning process functions similarly to an adaptive management process, but uses scenarios rather than computer models or management experiments to develop and test policy alternatives. One of the biggest shortcomings of scenario planning is the inability of participants to perceive their own assumptions (Keepin and Wynne 1984) and the potential consequences of being wrong. This problem cannot be completely avoided, but more robust scenarios can be created if a wide diversity of stakeholders and perspectives are included and if the exercise is repeated several times.

Conclusions

Human society depends on an array of services provided by ecosystems, including agro-ecosystems. However, agriculture has resulted in the serious degradation of the components and processes of many other ecosystems, including processes that are essential for food production. These include:

- River depletion and consequent degradation of downstream aquatic ecosystems, including effects on groundwater and fisheries.
- Drainage of wetlands and runoff or discharge of wastewater to surface water– and groundwater-dependent ecosystems.
- Groundwater depletion by overexploitation for irrigation, causing damage to groundwater-dependent ecosystems.
- Land degradation and alterations of local to regional climate from land-use changes.
- Pollution from overuse of nutrients and agrochemicals, with consequences for terrestrial and aquatic ecosystems and for human health because of water pollution.
- A worsening of water pollution problems by river depletion, decreasing possible river dilution, as illustrated in the tributaries to the Aral Sea and in the severe health problems caused to downstream populations.

There are four ways to respond to these adverse impacts:

- By rehabilitating lost or degraded ecosystems and ecological processes.
- By improving agricultural practices using existing and improved technology.
- By ensuring more careful forward planning that includes conscious striking of tradeoffs between water for food production and for other ecosystem services and dealing with uncertainty.
- By addressing the underlying social issues and divisions that affect how decisions are made in many communities, especially within poor rural communities that often disproportionately suffer the effects of environmental degradation.

It is also essential that unknown, poorly understood, or uncertain phenomena be brought into these tradeoffs. The social context for addressing these issues can be important, especially when such issues as culture, gender, health, and education come to the fore.

A more cautious approach toward water management and food production will be essential to ensure social and ecological sustainability

Where ecosystem degradation has not progressed too far, it may be possible to rehabilitate ecosystems, for instance, to reduce severe eutrophication of lakes and coastal waters or important wetlands and to secure, by reallocation, enough residual stream flow to restore environmental flows that support downstream ecosystems and ecosystem services. More essential are actions that focus on preventing further degradation and loss of important ecosystems.

Because food production will have to increase to alleviate undernutrition and to feed a projected 50% increase in the world population (before it stabilizes by the middle of the present century), many challenges remain for land and water managers. The type of responses available will differ depending on whether the effects of particular instances of ecosystem degradation are avoidable or unavoidable. Avoidable effects can be minimized largely through concerted responses, while unavoidable effects have to be considered when striking tradeoffs.

A catchment-based and integrated approach to land use, water, and ecosystems will be essential for a knowledge-based balancing of water among different ecological processes and the provision of ecosystem services. It will be necessary to develop the scientific and administrative capability and capacity to analyze the conditions necessary for securing social and ecological resilience to change in ecosystems, including in those that are particularly vulnerable to large or episodic events, such as drought, storms, and floods, and those that are subject to multiple and cumulative impacts. Climate change raises questions about how the future use of water and land for agriculture will constrain the ability of ecosystems to respond. That is, will water and land uses adversely affect ecosystem resilience and responses to climate change?

We are dependent on the ecological components and processes and ecosystem services that provide or support much of our food. Thus a more cautious approach toward water management and food production will be essential to ensure social and ecological sustainability. While food production will continue to be at the forefront of our endeavors to support human well-being, sustainability can be achieved only through a more conscious striking of tradeoffs between different interests. Underlying all must be a clear understanding of the vital role that ecosystems and ecosystem services play in supporting human well-being and the recognition that much past ecological change has undermined the provision of many vital ecosystem services, often with complex social and economic inequities.

Reviewers

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References

Acreman, M.C., and J.M. King. 2003. "Defining Water Requirements." In M. Dyson, G. Bergkamp, and J. Scanlon, eds., *Flow: The Essentials of Environmental Flows.* Gland, Switzerland, and Cambridge, UK: World Conservation Union.

Adams, W.M., R. Aveling, D. Brockington, B. Dickson, J. Elliott, J. Hutton, D. Roe, B. Vira, and W. Wolmer. 2004. "Biodiversity Conservation and the Eradication of Poverty." *Science* 306 (5699): 1146–49.

Agardy, T., and J. Alder. 2005. "Coastal Systems." In *Millennium Ecosystem Assessment.* Vol. 1, *Ecosystems and Human Well-being: Current State and Trends. Findings of the Conditions and Trends Working Group.* Washington, D.C.: Island Press.

Alam, M., and W. Kabir. 2004. "Irrigated Agriculture in Bangladesh and Possible Impact Due to Inter-Basin Water Transfer as Planned by India." Paper presented at the Annual Meeting of the American Society of Agricultural and Biological Engineers, 1–4 August, Ottawa, Canada.

Alexander, R.B., R.A. Smith, and G.E. Schwarz. 2000. "Effect of Stream Channel Size on the Delivery of Nitrogen to the Gulf of Mexico." *Nature* 403 (6771): 758–61.

Anderies, J.M. 2005. "Minimal Models and Agroecological Policy at the Regional Scale: An Application to Salinity Problems in Southeastern Australia." *Regional Environmental Change* 5 (1): 1–17.

Anderies, J.M., G. Cumming, M. Janssen, L. Lebel, J. Norberg, G. Peterson, and B. Walker. 2001. "A Resilience Centered Approach for Engaging Stakeholders about Regional Sustainability: An Example from the Goulburn Broken Catchment in Southeastern Australia." Technical Report. Commonwealth Scientific and Industrial Research Organisation Sustainable Ecosystems, Canberra, Australia.

Annear, T., I. Chisholm, H. Beecher, A. Locke, P. Aarrestad, C. Coomer, C. Estes, and others. 2002. *Instream Flows for Riverine Resource Stewardship.* Bozeman, Mont.: Instream Flow Council.

Arrow, K., B. Bolin, R. Costanza, P. Dasgupt, C. Folke, C.S. Holling, B-O. Jansson, S. Levin, K-G. Maler, C. Perrings, and D. Pimentel. 1995. "Economic Growth, Carrying Capacity, and the Environment." *Science* 268 (28 April): 520–21.

Balmford, A., A. Bruner, P. Cooper, R. Costanza, S. Farber, R.E. Green, M. Jenkins, and others. 2002. "Economic Reasons for Conserving Wild Nature." *Science* 297 (9 August): 950–53.

Baron, J.S., M.D. Hartman, T.G.F. Kittel, L.E. Band, D.S. Ojima, and R.B. Lammers. 1998. "Effects of Land Cover, Water Redistribution, and Temperature on Ecosystem Processes in the South Platte Basin." *Ecological Applications* 8 (4): 1037–51.

Baron, J.S., N. LeRoy Poff, P.L. Angermeier, C.N. Dahm, P.H. Gleick, N.G. Hairston, Jr., R.B. Jackson, C.A. Johnston, B.D. Richter, and A.D. Steinman. 2002. "Meeting Ecological and Societal Needs for Freshwater." *Ecological Applications* 12 (5): 1247–60.

Bennett, E.M., S.R. Carpenter, and N.F. Caraco. 2001. "Human Impact on Erodable Phosphorus and Eutrophication: A Global Perspective." *BioScience* 51 (3): 227–34.

Bennett, E.M., G.S. Cumming, and G.D. Peterson. 2005. "A Systems Model Approach to Determining Resilience Surrogates for Case Studies." *Ecosystems* 8 (8): 945–57.

Berg, H., M. Kilbus, and N. Kautsky. 1992. "DDT and Other Insecticides in the Lake Kariba Ecosystem." *Ambio* 21 (7): 444–50.

Berkes, F., and C. Folke. 1998. *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience.* Cambridge, UK: Cambridge University Press.

Berkes, F., J. Colding, and C. Folke, eds. 2003. *Navigating Social-ecological Systems: Building Resilience for Complexity and Change.* Cambridge, UK: Cambridge University Press.

Berndes, G. 2002. "Bioenergy and Water—The Implications of Large-scale Bioenergy Production for Water Use and Supply." *Global Environmental Change* 12 (4): 7–25.

Bosch, J.M., and J.D. Hewlett. 1982. "A Review of Catchment Experiments to Determine the Effect of Vegetation Changes on Water Yield and Evapotranspiration." *Journal of Hydrology* 55 (1–4): 3–23.

Bravo de Guenni, L. 2005. "Regulation of Natural Hazards: Floods and Fires." In *Millennium Ecosystem Assessment.* Vol. 1, *Ecosystems and Human Well-being: Current State and Trends. Findings of the Conditions and Trends Working Group.* Washington, D.C.: Island Press.

Briggs, S.V., and N. Taws. 2003. "Impacts of Salinity on Biodiversity—Clear Understanding or Muddy Confusion?" *Australian Journal of Botany* 51 (6): 609–17.

Bruijnzeel, L.A. 1990. *Hydrology of Moist Tropical Forests and Effects of Conversion: A State of Knowledge Review.* Paris and Amsterdam: United Nations Education, Scientific and Cultural Organization, International Hydrological Program, Humid Tropics Program, and Free University.

Bullock, A., and M. Acreman. 2003. "The Role of Wetlands in the Hydrological Cycle." *Hydrology and Earth System Sciences* 7 (3): 358–89.

Calder, I. 2005. *Blue Revolution: Integrated Land and Water Resource Management.* 2nd ed. London: Earthscan.

Carbonell, M., N. Nathai-Gyan, and C.M. Finlayson, eds. 2001. *Science and Local Communities: Strengthening Partnerships for Effective Wetland Management.* Memphis, Tenn.: Ducks Unlimited.

Carpenter, S.R. 2002. "Ecological Futures: Building an Ecology of the Long Now." *Ecology* 83 (8): 2069–83.

Carpenter, S.R., and M.G. Turner. 2000. "Hares and Tortoises: Interactions of Fast and Slow Variables in Ecosystems." *Ecosystems* 3 (6): 495–97.

Carpenter S.R., F. Westley, M.G. Turner. 2005. "Surrogates for Resilience of Social-Ecological Systems." *Ecosystems* 8 (8): 941–44.

Carpenter, S.R., B.H. Walker, J.M. Anderies, and N. Abel. 2001. "From Metaphor to Measurement: Resilience of What to What?" *Ecosystems* 4 (8): 765–81.

Carson, R. 1962. *Silent Spring.* Boston, Mass.: Houghton Mifflin.

Chase, T.N., R.A. Pielke, T.G.F. Kittel, J.S. Baron, and T.J. Stohlgren. 1999. "Potential Impacts on Colorado Rocky Mountain Weather Due to Land Use Changes on the Adjacent Great Plains." *Journal of Geophysical Research—Atmospheres* 104 (D14): 16673–90.

Coe, M.T., and J.A. Foley. 2001. "Human and Natural Impacts on the Water Resources of the Lake Chad Basin." *Journal of Geophysical Research—Atmospheres* 106 (D4): 3349–56.

Cohen, M. 2002. "Managing Across Boundaries: The Case of the Colorado River Delta." In P. Gleick, W.C.G. Burns, E.L. Chalecki, M. Cohen, K.K. Cushing, A.S. Mann, R. Reyes, G.H. Wolff, and A.K. Wong, eds., *The World's Water: 2002–03: The Biennial Report on Freshwater Resources.* Washington, D.C.: Island Press.

Cumming, G.S., and B.J. Spiesman. 2006. "Regional Problems need Integrated Solutions: Pest Management and Conservation Biology in Agroecosystems." *Biological Conservation* 131: 533–43.

Cumming, G.S., G. Barnes, S. Perz, M. Schmink, K.E. Sieving, J. Southworth, M. Binford, M.D. Holt, C. Stickler, and T.V. Holt. 2005. "An Exploratory Framework for the Empirical Measurement of Resilience." *Ecosystems* 8 (8): 975–87.

Daily**,** G.C., S. Alexander, P.R. Ehrlich, L. Goulder, J. Lubchenco, P.A. Matson, H.A. Mooney, S. Postel, S.H. Schneider, D. Tilman, and G.M. Woodwell. 1997. *Ecosystem Services: Benefits Supplied to Human Societies by Natural Ecosystems.* Washington, D.C.: Island Press.

Davidson**,** N.C., and D.A. Stroud. Forthcoming. "African-Eurasian Flyways: Current Knowledge, Population Status, and Future Challenges." In G. Boere, C. Galbraith, and D. Stroud, eds., *Waterbirds around the World.* Proceedings of the Global Flyways Conference 2004, Waterbirds around the World, Edinburgh, 3–8 April. London: CBI.

Davies, B.R., and J.A. Day. 1998. *Vanishing Waters.* Cape Town: UCT Press.

Davis, J.A., M. McGuire, S.A. Halse, D. Hamilton, P. Horwitz, A.J. McComb, R. Froend, M. Lyons, and L. Sim. 2003. "What Happens When You Add Salt: Predicting Impacts of Secondary Salinisation on Shallow Aquatic Ecosystems By Using an Alternative-States Model." *Australian Journal of Botany* 51 (6): 715–24.

Döll, P., and S. Siebert. 2002. "Global Modeling of Irrigation Water Requirements." *Water Resources Research* 38 (4): 1037.

Dybas, C.L. 2005. "Dead Zones Spreading in World Oceans." *BioScience* 55 (7): 552–57.

Dyson, M., G. Bergkamp, and J. Scanlon, eds. 2003. *The Essentials of Environmental Flows.* Gland, Switzerland, and Cambridge, UK: World Conservation Union.

Elder, S., and D. Schmidt. 2004. "Global Employment Trends for Woman, 2004." Employment Strategy Papers. International Labour Organisation, Geneva.

Elmqvist, T., C. Folke, M. Nystrom, G. Peterson, J. Bengtsson, B. Walker, and J. Norberg. 2003. "Response Diversity, Ecosystem Change, and Resilience." *Frontiers in Ecology and the Environment* 1 (9): 488–94.

Falconer, I.R. 2001. "Toxic Cyanobacterial Bloom Problems in Australian Waters: Risks and Impacts on Human Health." *Phycologia* 40 (3): 228–33.

Falkenmark, M. 1979. "Main Problems of Water Use and Transfer of Technology." *GeoJournal* 3 (5): 435–43.

———. 1999. Forward to the Future: A Conceptual Framework for Water Dependence. *Ambio* 28 (4): 356–61.

———. 2003. "Freshwater as Shared between Society and Ecosystems: From Divided Approaches to Integrated Challenges." *Philosophical Transactions of the Royal Society B* 358 (1440): 2037–49.

Falkenmark, M., and M. Lannerstad. 2005. "Consumptive Water Use to Feed Humanity—Curing a Blind Spot." *Hydrology and Earth System Sciences* 9 (1/2): 15–28.

Falkenmark, M., and J. Rockström. 1993. "Curbing Rural Exodus from Tropical Drylands." *Ambio* 22 (7): 427–37.

Farrington, P., and R.B. Salama. 1996. "Controlling Dryland Salinity by Planting Trees in the Best Hydrogeological Setting." *Land Degradation & Development* 7 (3): 183–204.

FAO and UNESCO (Food and Agriculture Organization and United National Educational, Scientific, and Cultural Organization). 2003. Digital Soil Map of the World and Derived Soil Properties. Rev.1. FAO, Rome. [www.fao.org/AG/agl/agll/dsmw.htm].

Fernandez, R.J., E.R.M. Archer, A.J. Ash, H. Dowlatabadi, P.H.Y. Hiernaux, J.F. Reynolds, C.H. Vogel, B.H. Walker, and T. Wiegand. 2002. "Degradation and Recovery in Socio-ecological Systems." In F. Reynolds and D.M. Stafford Smith, eds., *Global Desertification: Do Humans Cause Deserts?* Berlin: Dahlem University Press.

Finlayson, C.M., and R. D'Cruz. 2005. "Inland Water Systems." In R. Hassan, R. Scholes, and N. Ash, eds., *Ecosystems and Human Well-being: Current State and Trends: Findings of the Condition and Trends Working Group.* Washington, D.C.: Island Press.

Finlayson, C.M., H. Gitay, M.G. Bellio, R.A. van Dam, and I. Taylor. Forthcoming. "Climate Variability and Change and Other Pressures on Wetlands and Waterbirds—Impacts and Adaptation." In G. Boere, C. Galbraith, and D. Stround, eds., *Waterbirds around the World.* London: CBI Press.

Foley, J., R. DeFries, G.P. Asner, C. Barford, G. Bonan, S.R. Carpenter, F.S. Chapin, and others. 2005. "Global Consequences of Land Use." *Science* 309 (22 July): 570–74.

Folke, C., T. Hahn, P. Olsson, and J. Norberg. 2005. "Adaptive Governance of Social-Ecological Systems." *Annual Review of Environment and Resources* 30: 441–73.

Folke, C., Å. Jansson, J. Larsson, and R. Costanza. 1997. "Ecosystem Appropriation by Cities." *Ambio* 26 (3): 167–72.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C.S. Holling. 2004. "Regime Shifts, Resilience, and Biodiversity in Ecosystem Management." *Annual Review of Ecology, Evolution, and Systematics* 35: 557–81.

Folke C., S. Carpenter, T. Elmqvist, L. Gunderson, C.S. Holling., B. Walker, J. Bengtsson, F. Berkes, J. Colding, K. Danell, M. Falkenmark, L. Gordon, and others. 2002 *Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations*. Report for the Swedish Environmental Advisory Council, Ministry of the Environment, Stockholm.

Fu, C. 2003. “Potential Impacts of Human-induced Land Cover Change on East Asia Monsoon.” *Global and Planetary Change* 37 (3–4): 219–29.
Galloway, J.N., F.J. Dentener, D.G. Capone, E.W. Boyer, R.W. Howarth, S.P. Seitzinger, G. Asner, and others. 2004. “Global and Regional Nitrogen Cycles: Past, Present and Future.” *Biogeochemistry* 70 (2): 153–226.
Gammelsrod, T. 1992. “Variation in Shrimp Abundance on the Sofala Bank, Mozambique, and its Relation to the Zambezi River Runoff.” *Estuarine, Coastal and Shelf Science* 35 (1): 91–103.
Gitay, H., A. Suarez, R.T. Watson, and D.J. Dokken, eds. 2002. “Climate Change and Biodiversity.” IPCC Technical Paper V. Intergovernmental Panel on Climate Change, Washington, D.C.
Glover, D., and T. Jessup, eds. 1999. *Indonesia's Fires and Haze: The Cost of Catastrophe.* Singapore and Ottawa: Institute of South East Asian Studies and International Development Research Centre.
Gordon, L., M. Dunlop, and B. Foran. 2003. “Land Cover Change and Water Vapour Flows: Learning from Australia.” *Philosophical Transactions of the Royal Society B* 358 (1440): 1973–84.
Gordon, L.J., W. Steffen, B.F. Jönsson, C. Folke, M. Falkenmark, and Å. Johannesen. 2005. Human Modification of Global Water Vapor Flows from the Land Surface. *Proceedings of the National Academy of Sciences* 102 (21): 7612–17.
Green, P., C. J. Vörösmarty, M. Meybeck, J. Galloway, and B.J. Peterson. 2004. “Pre-industrial and Contemporary Fluxes of Nitrogen through Rivers: A Global Assessment Based on Typology.” *Biogeochemistry* 68 (1): 71–105.
Gunderson, L.H. 2001. “Managing Surprising Ecosystems in Southern Florida.” *Ecological Economics* 37 (3): 371–78.
Gunderson, L.H., and C.S. Holling. 2002. *Panarchy: Understanding Transformations in Human and Natural Systems.* Washington, D.C.: Island Press.
Gupta, S.K., and R.D. Deshpande. 2004. “Water for India in 2050: First-order Assessment of Available Options.” *Current Science* 86 (9): 1216–24.
Hall, S.J. 2002. “The Continental Shelf Benthic Ecosystem: Current Status, Agents for Change and Future Prospects.” *Environmental Conservation* 29 (3): 350–74.
He, C., S.-K. Cheng, and Y. Luo. 2005. “Desiccation of the Yellow River and the South Water Northward Transfer Project.” *Water International* 30 (2): 261–68.
Hertzman, T., and T. Larsson. 1999. *Lake Hornborga: The Return of a Bird Lake.* Publication 50. Wageningen, Netherlands: Wetlands International.
Hoffman, W.A., and R.B. Jackson. 2000. “Vegetation—Climate Feedbacks in the Conversion of Tropical Savanna to Grassland.” *American Meteorological Society* 13 (9): 1593–1602.
Holling, C.S. 1973. “Resilience and Stability of Ecological Systems.” *Annual Review of Ecology and Systematics* 4: 1–23
———. 1986. “The Resilience of Terrestrial Ecosystems: Local Surprise and Global Change.” In W.C. Clark and R.E. Munn, eds., *Sustainable Development of the Biosphere.* Cambridge, UK: Cambridge University Press.
Holling, C.S., and G.K. Meffe. 1996. “On Command-and-Control and the Pathology of Natural Resource Management.” *Conservation Biology* 10 (2): 328–37.
Holling, C.S., D.W. Schindler, B.W. Walker, and J. Roughgarden. 1995. “Biodiversity in the Functioning of Ecosystems: An Ecological Synthesis.” In C. Perrings, K.-G. Mähler, C. Folke, C.S. Holling, and B.-O. Jansson, eds., *Biodiversity Loss: Economic and Ecological Issues.* Cambridge, UK: Cambridge University Press.
Hollis, G.E. 1994. “Halting and Reversing Wetland Loss and Degradation: A Geographical Perspective on Hydrology and Land Use.” Thomas Telford Services and Institution of Engineers, London.
International Council for Science. 2002. *Biodiversity, Science and Sustainable Development.* Series on Science for Sustainable Development 10. Paris.
Italy, Ministry for the Environment and Territory, and Free Iraq Foundation. 2004. The New Eden Project: Final Report. Paper presented at the United Nations Commission for Sustainable Development CSD-12 meeting April 14–30, New York. [www.edenagain.org/publications/pdfs/newedenfinalreportcsd12rev0.pdf].
IUCN (World Conservation Union). 2003. The Pangani River Basin. A Situation Analysis. Gland, Switzerland.
Jackson, R.B., E.G. Jobbágy, R. Avissar, S. Baidya Roy, D. Barrett, C.W. Cook, K.A. Farley, D.C. le Maitre, B.A. McCarl, and B.C. Murray. 2005. “Trading Water for Carbon with Biological Carbon Sequestration.” *Science* 310 (23 December): 1944–47.
Jansson, Å., C. Folke, J. Rockström, and L. Gordon. 1999. “Linking Freshwater Flows and Ecosystem Services Appropriated by People: The Case of the Baltic Sea Drainage Basin.” *Ecosystems* 2 (4): 351–66.
Jansson, A.M., M. Hammer, C. Folke, and R. Costanza, eds. 1994. *Investing in Natural Capital: The Ecological Economics Approach to Sustainability.* Washington, D.C.: Island Press.
Jewitt, G. 2002. “The 8%–4% Debate: Commercial Afforestation and Water Use in South Africa.” *Southern African Forestry Journal* 194 (2): 1–6.

Junk, W. 2002. "Long-term Environmental Trends and the Future of Tropical Wetlands." *Environmental Conservation* 29 (4): 414–435.
Kabat, P., M. Claussen, P.A. Dirmeyer, J.H.C. Gash, L. Bravo de Guenni, M. Meybeck, R.A. Pielke, Sr., C.J. Vörösmarty, R.W.A. Hutjes, and S. Lütkemeier. 2004. *Vegetation, Water, Humans and the Climate: A New Perspective on an Interactive System.* Berlin: Springer-Verlag.
Keepin, B., and B. Wynne. 1984. "Technical Analysis of IIASA Energy Scenarios." *Nature* 312 (5996): 691–95.
King, J.M., C. Brown, and H. Sabet. 2003. "A Scenario-based Holistic Approach to Environmental Flow Assessments for Rivers." *River Research and Applications* 19 (5/6): 619–39.
King, J.M., R.E. Tharme, and H. Sabet. 2000. "Environmental Flow Assessments for Rivers: Manual for the Building Block Methodology." Water Research Commission, Pretoria.
Kremen, C. 2005. "Managing for Ecosystem Services: What Do We Need to Know About Their Ecology?" *Ecology Letters* 8 (5): 468–479.
Kremen, C., N.M. Williams, and R.W. Thorp. 2002. "Crop Pollination From Native Bees at Risk from Agricultural Intensification." *Proceedings of the National Academy of Sciences* 99 (26): 16812–16.
Kura, Y., C. Revenga, E. Hoshino, and G. Mock. 2004. *Fishing for Answers.* Washington D.C.: World Resources Institute.
Lansing, J.S. 1991. *Priests and Programmers: Technologies of Power in the Engineered Landscape of Bali.* Princeton, N.J.: Princeton University Press.
Le Maitre, D.C., B.W. van Wilgen, R.A. Chapman, and D.H. McKelly. 1996. "Invasive Plants and Water Resources in the Western Cape Province, South Africa: Modelling the Consequences of a Lack of Management." *Journal of Applied Ecology* 33 (1): 161–172.
Lee, K. 1993. *Compass and Gyroscope: Integrating Science and Politics for the Environment.* Washington, D.C.: Island Press.
Lemly, A.D., R.T. Kingsford, and J.R. Thompson. 2000. "Irrigated Agriculture and Wildlife Conservation: Conflict on a Global Scale." *Environmental Management* 25 (5): 485–512.
Lemoalle, J. 2003. "Lake Chad: A Changing Environment." In J.C.J. Nihoul, P.O. Zavialov, and P.P. Micklin, eds, *Dying and Dead Seas.* NATO Advanced Research Workshop, Advanced Study Institute Series, Dordrecht, Netherlands: Kluwer Publishers.Levin, S. 1999. *Fragile Dominion: Complexity and the Commons.* Reading, Mass.: Perseus Books.
Levin, S.A. 1999. *Fragile Dominion: Complexity and the Commons.* Reading, Mass.: Perseus Books.
L'vovich, M.I. 1979. *World Water Resources and their Future.* Chelsea, UK: LithoCrafters Inc.
Lukatelich, R. J., and A.J. McComb. 1986. "Nutrient Levels and the Development of Diatom and Blue-Green Algal Blooms in a Shallow Australian Estuary.*" Journal of Plankton Research* 8 (4): 597–618.
Magadza, C.H.D. 1995. "Special Problems in Lakes/Reservoir Management in Tropical Southern Africa." Presented at the 6th International Conference on the Conservation and Management of Lakes, 23–27 October, University of Tsukuba, Japan.
Marland, G., R.A. Pielke, Sr., M. Apps, R. Avissar, R.A. Betts, K.J. Davis, P.C. Frumhoff, S.T. Jackson, and others. 2003. "The Climatic Impacts of of Land Surface Change and Carbon Management, and the Implications for Climate-Change Mitigation Policy." *Climate Policy* 3 (2): 149–57.
McCulloch, J.S.G., and M. Robinson. 1993. "History of Forest Hydrology." *Journal of Hydrology* 150 (2–4): 189–216.
McNeely, J.A., and S.J. Scherr. 2003. *Ecoagriculture: Strategies to Feed the World and Save Wild Biodiversity*. Washington, D.C.: Island Press.
MEA (Millennium Ecosystem Assessment). 2003. *Ecosystems and Human Well-being: A Framework for Assessment.* Washington D.C.: Island Press.
———. 2005a. *Ecosystems and Human Well-being: Health Synthesis.* Washington, D.C.: World Resources Institute.
———. 2005b. *Ecosystems and Human Well-being: Wetlands and Water Synthesis.* Washington, D.C.: World Resources Institute.
———. 2005c. *Millennium Ecosystem Assessment Synthesis Report.* Washington D.C.: Island Press.
Meybeck, M., and A. Ragu. 1997. "Presenting the GEMS-GLORI, A Compendium of World River Discharge to the Oceans." In B. Webb, ed., *Freshwater Contamination. Proceedings of a Symposium Held During the Fifth IAHS Scientific Assembly at Rabat, Morocco, April–May 1997.* Publication 243. Wallingford, UK: International Association of Hydrological Sciences.
Milliman, J.D. 1991. "Flux and Fate of Fluvial Sediment and Water in Coastal Seas." In R.F.C. Mantoura, J.-M. Martin, and R. Wollast, eds., *Ocean Margin Processes in Global Change.* Chichester, UK: John Wiley & Sons.
Mirza, M.M.Q. 1998. "Diversion of the Ganges Water at Farakka and its Effects on Salinity in Bangladesh." *Environmental Management* 22 (5): 711–22.
Molden, D., and C. de Fraiture. 2004. "Investing in Water for Food, Ecosystems and Livelihoods." Comprehensive Assessment of Water Management in Agriculture Blue Paper. International Water Management Institute, Colombo.

Nemani, R.R., S.W. Running, R.A. Pielke, and T.N. Chase. 1996. "Global Vegetation Cover Changes from Coarse Resolution Satellite Data." *Journal of Geophysical Research* 101 (D3): 7157–62.

North American Waterfowl Management Plan. 2004. *Strengthening the Biological Foundation*. Ottawa, Washington, D.C., and Mexico City: Environment Canada; US Department of the Interior, Fish and Wildlife Services; and Secretaria de Medio Ambente Recursos Naturales.

OECD (Organisation for Economic Co-operation and Development) 1996. *Guidelines for Aid Agencies for Improved Conservation and Sustainable Use of Tropical and Subtropical Wetlands.* Paris.

Olsson, P., C. Folke, and T. Hahn. 2004. "Social-ecological Transformation for Ecosystem Management: The Development of Adaptive Co-management of a Wetland Landscape in Southern Sweden." *Ecology and Society* 9 (4): 2.

Oyama, M.D., and C.A. Nobre. 2003. "A New Climate-Vegetation Equilibrium State for Tropical South America." *Geophysical Research Letters* 30 (23) 2199–203.

Page, S.E., F. Siegert, J.O. Rieley, H.D. Boehm, A. Jaya, and S. Limin. 2002. "The Amount of Carbon Released from Peat and Forest Fires in Indonesia during 1997." *Nature* 420 (6911): 61–65.

Pala, C. 2006. "Once a Terminal Case, the Aral Sea Shows New Signs of Life." *Science* 312 (5771): 183.

Partow, H. 2001. *The Mesopotamian Marshlands: Demise of an Ecosystem.* Nairobi: United Nations Environment Programme.

Peterson, G.D., G.S. Cumming, and S.R. Carpenter. 2003. "Scenario Planning: A Tool for Conservation in an Uncertain World." *Conservation Biology* 17 (2): 358–66.

Pielke, R.A., T.J. Lee, J.H. Copeland, J.L. Eastman, C.L. Ziegler, and C.A. Finley. 1997. "Use of USGS–Provided Data to Improve Weather and Climate Simulations." *Ecological Applications* 7 (1): 3–21.

Pielke, R.A., R.L. Walko, L. Steyaert, P.L. Vidale, G.E. Liston, W.A. Lyons, and T.N. Chase. 1999. "The Influence of Anthropogenic Landscape Changes on Weather in South Florida." *Monthly Weather Review* 127 (7): 1663–73.

Pielke, R.A., Sr., R. Avissar, M. Raupach, A.J. Dolman, X. Zeng, and A.S. Denning. 1998. "Interactions between the Atmosphere and Terrestrial Ecosystems: Influence on Weather and Climate." *Global Change Biology* 4 (5): 461–75.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. "The Natural Flow Regime: A Paradigm for River Conservation and Restoration." *Bioscience* 47 (11): 769–84.

Postel, S. 1996. *Last Oasis: Facing Water Scarcity.* New York: W.W. Norton & Company.

———. 1999. *Pillar of Sand: Can the Irrigation Miracle Last?* New York: W.W. Norton & Company.

Postel, S., and S.R. Carpenter. 1997. "Freshwater Ecosystem Services." In G. Daily, ed., *Nature's Services*. Washington, D.C.: Island Press.

Rahman, M.M, M.Q. Hassan, M. Islam, and S.Z.K.M. Shamsad. 2000. "Environmental Impact Assessment on Water Quality Deterioration Caused by the Decreased Ganges Outflow and Saline Water Intrusion in South-western Bangladesh." *Environmental Geology* 40 (1–2): 31–40.

Revenga, C., J. Brunner, N. Henniger, K. Kassem, and R. Payner. 2000. *Pilot Analysis of Global Ecosystems, Freshwater Systems.* Washington, D.C.: World Resources Institute.

Richardson, C.J., P. Reiss, N.A. Hussain, A.J. Alwash, and D.J. Pool. 2005. "The Restoration Potential of the Mesopotamian Marshes of Iraq." *Science* 307 (5713): 1307–11.

Richter, B.D., R. Mathews, D.L. Harrison, and R. Wigington. 2003. "Ecological Sustainable Water Management: Managing River Flows for Ecological Integrity." *Ecological Applications* 13 (1): 206–24.

Rogers, K., and H. Biggs. 1999. "Integrating Indicators, Endpoints and Value Systems in Strategic Management of the Rivers of the Kruger National Park." *Freshwater Biology* 41 (2): 439–52.

Salati, E., and C.A. Nobre. 1991. "Possible Climatic Impacts of Tropical Deforestation." *Climate Change* 19 (1–2): 177–96.

Savenije, H.H.G. 1995. "New Definitions for Moisture Recycling and the Relation with Land-use Changes in the Sahel." *Journal of Hydrology* 167 (1): 57–78.

———. 1996. "Does Moisture Feedback Affect Rainfall Significantly?" *Physical Chemistry of the Earth* 20 (5–6): 507–51.

Scheffer, M., S. Carpenter, J. A. Foley, C. Folke, and B. Walker. 2001. "Catastrophic Shifts in Ecosystems." *Nature* 413 (11 October): 591–96.

Shiklomanov, I.A., and J. Rodda. 2003. *World Water Resources at the Beginning of the 21st Century.* Paris: United Nations Educational, Scientific and Cultural Organization.

Silvius, M.J., M. Oneka, and A. Verhagen. 2000. "Wetlands: Lifeline for People at the Edge." *Physical Chemistry of the Earth B* 25 (7–8): 645–52.

Silvius, M.J., B. Setiadi, W.H. Diemont, F. Sjarkowi, H.G.P. Jansen, H. Siepel, J.O. Rieley, A. Verhagen, A. Beintema, L. Burnhill, and S.H. Limin. 2003. "Financial Mechanisms for Poverty-Environment Issues. The Bio-rights System." Alterra and Wetlands International, Wageningen, Netherlands.

SIWI (Stockholm International Water Institute), IFPRI (International Food Policy Research Institute), IUCN (World Conservation Union), and IWMI (International Water Management Institute). 2005. *Let It Reign: The New Water Paradigm for Global Food Security.* Final report to CSD-13. Stockholm: Stockholm International Water Institute.
Smakhtin, V., C. Revenga, and P. Döll. 2004. "Taking into Account Environmental Water Requirements in Global-scale Water Resources Assessments." Comprehensive Assessment of Water Management in Agriculture. International Water Management Institute, Colombo.
Snaddon, C.D., B.R. Davies, and M.J. Wishart. 1999. "A Global Overview of Inter-basin Water Transfer Schemes, with an Appraisal of their Ecological, Socio-Economic and Socio-Political Implications, and Recommendations for their Management." Water Research Commission Technology Transfer Report TT 120/00. Water Research Commission, Pretoria.
Steffen, W., A. Sanderson, P.D. Tyson, J. Jäger, P.A. Matson, B. Moore, F. Oldfield, K. Richardson, H.J. Schellnhuber, B.L. Turner, and R.J. Wasson. 2004. *Global Change and the Earth System: A Planet Under Pressure.* Berlin: Springer-Verlag.
Strehlow, K., J. Davis, L. Sim, J. Chambers, S. Halse, D. Hamilton, P. Horwitz, A. McComb, and R. Froend. 2005. "Temporal Changes between Ecological Regimes in a Range of Primary and Secondary Salinised Wetlands." *Hydrobiologia* 552 (1): 17–31.
Taylor, G.J., D.J. Baird, and A.M.V.M. Soares. 2002. "Ecotoxicology of Contaminants in Tropical Wetlands: The Need for Greater Ecological Relevance in Risk Assessment." *SETAC Globe* 3 (1): 27–28.
Tharme, R.E. 2003. "A Global Perspective on Environmental Flow Assessment: Emerging Trends in the Development and Application of Environmental Flow Methodologies for Rivers." *River Research and Applications* 19 (5–6): 397–441.
Tilman, D., J. Knops, D. Wedin, P. Reich, M. Ritchie, and E. Siemann. 1997. "The Influence of Functional Diversity and Composition on Ecosystem Processes." *Science* 277 (5330): 1300–02.
Trenberth, K.E. 1999. "Conceptual Framework for Changes of Extremes of the Hydrological Cycle with Climate Change." *Climatic Change* 42 (1): 327–39.
UNEP (United Nations Environment Programme). 2002. *Africa Environment Outlook: Past, Present and Future Perspectives.* Hertfordshire, UK: Earthprint.
UNESCO (United Nations Educational, Scientific and Cultural Organization). 2000. *Water Related Vision for the Aral Sea Basin for the Year 2025.* Paris.
Van Dam, R., H. Gitay, M. Finlayson, N.J. Davidson, and B. Orlando. 2002. "Climate Change and Wetlands: Impacts, Adaptation and Mitigation." Background document DOC.SC26/COP8–4 for the 26th Meeting of the Standing Committee of the Convention on Wetlands (Ramsar Convention), 3–7 December, Gland, Switzerland.
Van den Brink, P.J., S.N. Sureshkumar, M.A. Daam, I. Domingues, G.K. Milwain, W.H.J. Beltman, M. Warnajith, P. Perera, and K. Satapornvanit. 2003. Environmental and Human Risks of Pesticide Use in Thailand and Sri Lanka: Results of a Preliminary Risk Assessment. Alterra-rapport 789. MAMAS Report Series No. 3/2003. Green World Research. Wageningen, Netherlands: Alterra.
Verhoeven, J.T.A., B. Arheimer, C. Yin, and M.M. Hefting. 2006. "Regional and Global Concerns over Wetlands and Water Quality." *Trends in Ecology and Evolution*.21 (2): 96–103.
Vörösmarty, C.J., and D. Sahagian 2000. "Anthrogenic Disturbance of the Terrestrial Water Cycle." *BioScience* 50: 753–65.
Vörösmarty, C.J., C. Lévêque, and C. Revenga. 2005. "Fresh Water." In R. Hassan, R. Scholes, and N. Ash, eds., *Ecosystems and Human Well-being: Current State and Trends: Findings of the Condition and Trends Working Group.* Washington, D.C.: Island Press.
Vörösmarty, C.J., M. Meybeck, B. Fekete, K. Sharma, P. Green, and J. Syvitski. 2003. "Anthropogenic Sediment Retention: Major Global Impact from Registered River Impoundments." *Global and Planetary Change* 39 (1–2): 169–90.
Walling, D.E., and D. Fang. 2003."Recent trends in the suspended sediment loads of the world's rivers." *Global and Planetary Change* 39 (1–2): 111–26.
Walters, C.J. 1986. *Adaptive Management of Renewable Resources.* New York: MacMillan Publishing Co.
Walters, C.J., L.H. Gunderson, and C.S. Holling. 1992. "Experimental Policies for Water Management in the Everglades." *Ecological Applications* 2 (2): 189–202.
Walters, C., J. Korman, L.E. Stevens, and B. Gold. 2000. "Ecosystem Modeling for Evaluation of Adaptive Management Policies in the Grand Canyon." *Conservation Ecology* 4 (2): 1.
WCD (World Commission on Dams). 2000. *Dams and Development: A New Framework for Decision-Making.* London: Earthscan.
Wester, P., C.A. Scott, and M. Burton. 2005. "River Basin Closure and Institutional Change in Mexico's Lerma-Chapala Basin." In M. Svendsen, ed., *Irrigation and River Basin Management: Options for Governance and Institutions.* Wallingford, UK: CABI Publishing.
Williams, W.D. 2002. "Environmental Threats to Salt Lakes and the Likely Status of Inland Saline Wetlands by 2025." *Environment Conservation* 29 (2): 154–67.

Wollheim, W.M., B.J. Peterson, L.A. Deegan, J.E. Hobbie, B. Hooker, W.B. Bowden, K.J. Edwardson, D.B. Arscott, A.E. Hershey, and J. Finlay. 2001. "Influence of Stream Size on Ammonium and Suspended Particulate Nitrogen Processing." *Limnology and Oceanography* 46 (1): 1–13.

Wooster, M.J., and N. Strub. 2002. "Study of the 1997 Borneo Fires: Quantitative Analysis Using Global Area Coverage (GAC) Satellite Data." *Global Biogeochemical Cycles* 16 (1): 1009.

WMO (World Meteorological Organization). 1997. *Comprehensive Assessment of the Freshwater Resources of the World.* Stockholm: World Meteorological Organization and Stockholm Environment Institute.

Wösten, J.H.M., J. van den Berg, P. van Eijk, G.J.M. Gevers, W.B.J.T. Giesen, A. Hooijer, A. Idris, P.H. Leenman, D.S. Rais, C. Siderius, M.J. Silvius, N. Suryadiputra, and I.T. Wibisono. 2006. "Interrelationships between Hydrology and Ecology in Fire Degraded Tropical Peat Swamp Forests." *International Journal of Water Resources Development* 22 (1): 157–74.

WRI (World Resources Institute), UNDP (United Nations Development Programme), UNEP (United Nations Environment Programme), and World Bank. 2005. *World Resources 2005: The Wealth of the Poor—Managing Ecosystems to Fight Poverty.* Washington, D.C.: World Resources Institute.

WWF. 2006. *Payments for Environmental Services: An Equitable Approach for Reducing Poverty and Conserving Nature.* Gland, Switzerland.

Zavaleta, E. 2000. "The Economic Value of Controlling an Invasive Shrub." *Ambio* 29 (8): 462–67.

Zheng, X., and E.A.B. Eltathir. 1998. "The Role of Vegetation in the Dynamics of West African Monsoons." *Journal of Climate* 11 (8): 2078–96.

Zwarts, L., P. Van Beukering, B. Kone, E. Wymenga, and D. Taylor. 2006. "The Economic and Ecological Effects of Water Management Choices in the Upper Niger River: Development of Decision Support Methods." *International Journal of Water Resources Development* 22 (1): 135–56.