Chapter 12

Interactions among Ecosystem Services

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Main Messages

Ecosystem service trade-offs arise from management choices made by humans, who intentionally or otherwise change the type, magnitude, and relative mix of services provided by ecosystems. Such trade-offs will be critical considerations for policy-makers over the next 50 years. Trade-offs can be classified in terms of their temporal and spatial scales, and their degree of reversibility. They can also be classified in terms of the type of service targeted and the type of service "traded-off." Identifying trade-offs allows policy-makers to understand the long-term effects of preferring one ecosystem service over another and the consequences of focusing only on the present provision of a service rather than its future.

Major decisions in the next 50–100 years will have to be made on the current use of nonrenewable resources and their future use. Important specific trade-offs are those between agricultural production and water quality, land use and biodiversity, water use and aquatic biodiversity, and current water use for irrigation and future agricultural production. These overarching trade-offs appear consistently throughout all four Millennium Ecosystem Assessment scenarios. Technological or institutional advances that mitigate such trade-offs will improve ecosystem services and simplify the factors that must be considered in making decisions.

Synergistic interactions allow for the simultaneous enhancement of more than one ecosystem service. Since increasing the supply of one ecosystem service can enhance the supply of others (for example, forest restoration may lead to improvements in several cultural, provisioning, and regulating ecosystem services), successful management of synergisms is a key component of any strategy aimed at increasing the supply of ecosystem services for human well-being.

Numerous trade-offs exist that are unknown and unanticipated by people acting within all four MA scenarios. These trade-offs may not manifest until long after the initial decisions are made, even though they are already affecting the mix of ecosystem services provided. Synergisms and trade-offs also often have unanticipated effects on secondary services, not just the primary ecosystem services that we intend to affect with a decision.

Because trade-offs exist and because policy-makers must make decisions about ecosystem services, they are sometimes forced to make decisions that prefer some ecosystem services over others. In general, across all four MA scenarios and case study examples, trade-off decisions showed a preference for provisioning, regulating, or cultural services (in that order). Supporting services are more likely to be "taken for granted."

Slowly changing variables, which tend to underlie supporting services, are often ignored by policy-makers in ways that seriously undermine the long-term existence of provisioning ecosystem services. Slowly changing variables are difficult to understand and rarely quantified within ecosystem models, and their change is difficult to detect. Examples of slowly changing variables or processes include geologic weathering, soil formation and condition, populations of long-lived organisms, and genetic diversity of organisms that directly affect people. Monitoring programs that focus on slowly changing variables may help decision-makers value supporting services appropriately.

Each of the MA scenarios takes a different approach to trade-offs. In Global Orchestration, society gives preference to provisioning ecosystem services. In Order from Strength, present use of ecosystem services is favored over potential future uses. Under Adapting Mosaic, there is no dominant type of trade-off because most decisions are made locally. However, the approach to trade-offs becomes more ecologically sound, as previously unidentified trade-offs and synergisms are revealed through learning and incorporated into decision-making. There is greater opportunity for institutional solutions to trade-off problems in Adapting Mosaic. In TechnoGarden, cultural services are undervalued and often traded-off in management decisions. There is greater opportunity for technological solutions to trade-off problems in TechnoGarden.

Current models are unable to capture all the interactions and secondary effects of trade-offs and synergisms; thus the quantitative model results are a crude lower boundary of the impact of potential ecosystem service trade-offs. Cultural ecosystem services are almost entirely unquantified in scenario modeling; therefore, the calculated model results do not fully capture losses of these services that occur in the scenarios. The quantitative scenario models primarily capture the services that are perceived by society as more important—provisioning and regulating ecosystem services—and thus do not fully capture trade-offs of cultural and supporting services.

12.1 Introduction

Ecosystem services do not operate in isolation. They interact with one another in complex, often unpredictable ways. Many services are provided by ecosystems in interdependent "bundles." (See Chapter 3.) By choosing one bundle, other services may be reduced or foregone. For example, impounding streams for hydroelectric power may have negative consequences for downstream food provisioning by fisheries. Knowledge of the interactions among ecosystem services is necessary for making sound decisions about how society manages the services provided by nature.

The models that we use to understand and make decisions about ecosystems are often inadequate for addressing interactions of multiple ecosystem services (Sterman and Sweeney 2002). In contrast, because of their nature as complex, logical stories, scenarios consider as many interactions as possible. Therefore, the Millennium Ecosystem Assessment scenarios, which focus on the future of ecosystem services and human well-being, provide an ideal opportunity to examine the interactions among ecosystem services. (For a short description of the four scenarios, please see the Summary for Decision-makers.)

This chapter explores two specific policy-relevant interactions among ecosystem services: synergisms and trade-offs. By highlighting these two types of interactions, we are recognizing that although some properties of ecosystems may be susceptible to human intervention and control, others are not; understanding this distinction is essential if we are to manage ecosystem services to maximize human well-being.

In the context of the provision of ecosystem services, a synergism is defined as a situation in which the combined effect of several forces operating on ecosystem services is greater than the sum of their separate effects (adapted from Begon et al. 1996). In other words, a synergism occurs when ecosystem services interact with one another in a multiplicative or exponential fashion. Synergisms can have positive and negative effects. Synergistic interactions pose a major challenge to the management of ecosystem services because the strength and direction of such interactions remains virtually unknown (Sala et al. 2000). But synergisms also offer opportunities for enhanced management of such services. For example, if society chooses to improve the delivery of an ecosystem service, and this service interacts in a positive and synergistic way with another ecosystem service, the resulting overall benefit could be much larger than the benefit provided by one ecosystem service alone.

Trade-offs, in contrast, occur when the provision of one ecosystem service is reduced as a consequence of increased use of another ecosystem service. Trade-offs seem inevitable in many circumstances and will be critical for determining the outcome of environmental decisions. In some cases, a trade-off may be the consequence of an explicit choice; but in others, trade-offs arise without premeditation or even awareness that they are taking place. These unintentional trade-offs happen when we are ignorant of the interactions among ecosystem services or when we are familiar with the interactions but our knowledge about how they work is incorrect or incomplete. As human societies transform ecosystems to obtain greater provision of specific services, we will undoubtedly diminish some to increase others.

Often, interactions among ecosystem services simply exist, and policy-makers cannot choose whether to allow a trade-off or not. For example, if we devote a particular piece of land to timber harvesting, its value for nature recreation will probably decrease. Although this will happen regardless of whether we acknowledge that a choice was made, timber harvesting techniques are susceptible to improvements that may improve recreation opportunities. Many trade-offs can be modified by technology or by human or institutional services that regulate access to and distribution of ecosystem services. For instance, a trade-off may exist between agricultural production and species richness, yet we can use technological advances to increase agricultural production and make our farms more diverse at the same time.

Decisions relating to natural resource management often revolve around ecosystem service trade-offs and involve services that interact synergistically. Robust decisions take careful account of their impacts on a range of ecosystem services and do not focus only on a single service of greatest apparent interest. A better knowledge of trade-offs and synergisms would simplify environmental decision-making. To illustrate ecosystem service trade-offs and their consequences for society, this chapter draws on the results of the scenario analyses and a variety of published case studies. We focus on synergisms when opportunities for the improved delivery of multiple ecosystem services simultaneously exist.

This chapter considers the interactions among ecosystem services in five major sections. First, we examine the results of both the quantitative and qualitative MA scenario models to derive an understanding of the major trade-offs common across all scenarios and the different trade-offs and synergisms illustrated by the scenarios. We also explore the links between ecosystem service trade-offs, synergisms, and the Millennium Development Goals. Second, we present a series of case studies from the literature and use the results of these case studies to develop two different approaches for understanding the nature of trade-offs. Third, we combine the results from the scenarios and the case studies to propose some characteristics that are common to all trade-off decisions. Finally, we illustrate some of the common dilemmas faced when making ecosystem service management decisions and discuss some of the problems of using modeling results when examining ecosystem service trade-offs.

12.2 Interactions among Ecosystem Services in the Scenarios

To help understand ecosystem service interactions, we propose a system with three axes: spatial scale, temporal scale, and irreversibility. Each interaction can then be classified in one of two categories for each one of the axes. (See Figure 12.1.) *Spatial scale* refers to whether the effects of the synergism or trade-off are felt locally or at a distant location. *Temporal scale* refers to whether the effects take place relatively rapidly or slowly. *Irreversibility* expresses the likelihood that the perturbed ecosystem service may return to its original state if the perturbation ceased.

Because many management actions affect more than one ecosystem service at a time and may operate at different scales simultaneously, it can be difficult to classify ecosystem service interactions in a single category. At the same time, knowledge of the different scales at which policies should be targeted is a key component of managing ecosystem services. Therefore, creating classifications is an important first step toward improving our understanding of the interactions among ecosystem services.

Classification schemes allow a manager to think strategically about the use of ecosystem services, understand the nature of the ecosystem services being considered, be aware of the spatial and temporal scale at which the ecosystem services operates, and determine how far-reaching the effects of particular decisions can be. The policy-maker can tailor management decision to the appropriate scale to mitigate any negative effects and thereby produce ''win-win'' solutions.

At many points throughout the scenario analysis, quantitative and qualitative results reflect the different underlying decision-making paradigms within a particular scenario.

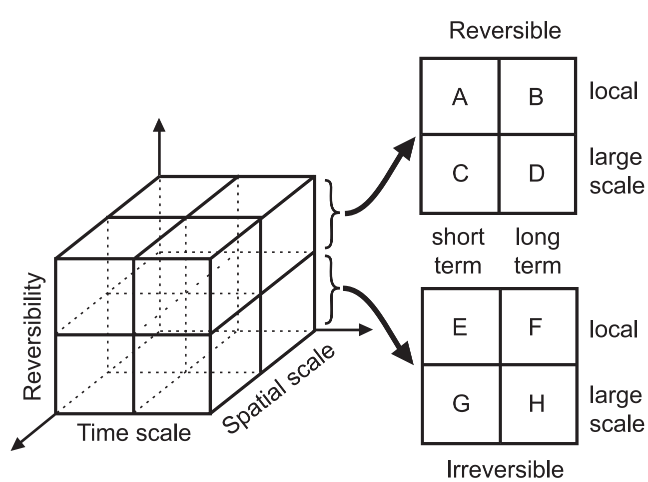

Figure 12.1. Eight Categories of Ecosystem Service Trade-offs, Classified According to Spatial and Temporal Scales and Degree of Reversibility

Despite the difference of worldviews represented in the scenarios, some major trade-offs are common to all of them, with major implications for the continuing delivery of supporting and regulating ecosystem services. The ecosystem service trade-offs that are present across the scenarios may be a result of the underlying assumptions of either the scenarios or the models used. However, cross-scenario commonalities also suggest that these trade-offs are likely to occur regardless of the path that society takes, largely because such trade-offs are driven by the short-term provisioning services that are necessary to assure human well-being. In each case, the scenarios show that our management and decisions about future trade-offs will have a significant effect on the provision of ecosystem services (and hence, human well-being) by the year 2050.

12.2.1 Agricultural Production, Water Quality, and Aquatic Habitats and Species

Agricultural production shows an inverse relationship with water quality and quantity: as we increase agricultural production, the quality of water and the quantity available tend to decrease. (See Chapter 9.) In general, increased efficiency of agricultural production has been accomplished through technology and the increased use of water, nutrients, and pesticides. Because the supply of water is finite, water used for agriculture cannot be used for other purposes. Thus we trade off having water available for other uses in order to increase agricultural production. Nutrients and pesticides can run off from agricultural fields into nearby streams, rivers, lakes, and estuaries, leading to declines in water quality. Thus, use of nutrients and pesticides to increase agricultural production can lead to critical declines in water quality. The negative impacts on water quality often propagate downstream. In the scheme presented in Figure 12.1, such water quality trade-offs can be local or large-scale, short-term or long-term, and are probably not reversible in short time frames (categories A-D). The case of agriculture and hypoxia in the Gulf of Mexico provides a very compelling example of the complexities involved in managing the impacts of agrochemicals. (See Chapter 8.)

Greater use of the world's water supply for agricultural production may improve basic food production and human health in many places. However, increases in pollution and water shortages caused by more-intensive agriculture may make many of these regions more vulnerable to surprises, such as drought, eutrophication, or floods that overwhelm sewage treatment plants. One unexpected consequence of agricultural intensification and climate change is that many rivers will have higher discharge rates, becoming more prone to flooding and drying, with few big differences between scenarios. Many areas that are already water-limited will face further water availability stress and will be more susceptible to environmental perturbations such as drought. These regions may find themselves facing water shortages or water that is undrinkable. Evolution of technology is projected to help the current situation, but only slightly; water limitations will be a concern regardless of which scenario is considered.

In all scenarios, higher income and increasing investments in technology lead to intensification and expansion of agriculture. (See Chapter 9.) Further, the increases in total agricultural production lead to the expansion of irrigated farmland, increased water stress, and increases in the volume of polluted water. Provisioning services such as access to water are traded off for increases in food supply. The heavy emphasis on food production leads to a multitude of uncertainties in relation to the integrity of other ecosystem services.

Changes in water quality also have negative impacts on freshwater biodiversity. As in the trade-off between food production and terrestrial plant biodiversity (described in the next section), short-term gains in water access that initially increase human well-being will lead to reductions in aquatic habitat (and biodiversity) and ultimately to greater regional vulnerability to water shortages (see Chapter 11) and a decline in human well-being. The decrease in available fresh water also has implications for the future productivity of freshwater fisheries, waste removal, and human settlement patterns. (See Chapter 10.)

According to the scenarios, fresh water is a commodity that will require significant planning and conservation in the future to assure that demands do not outstrip the necessary supply. In almost all instances, the scenarios suggest that numerous trade-offs will have significant impact on the quantity and quality of fresh water available for all aspects of human well-being. When making choices about the short-term provisioning needs gained from agricultural production, managers who incorporate the realities of limited freshwater supply in their models for management planning will be more successful than those who do not. Technologies that promote or conserve fresh water, similar to those emphasized in TechnoGarden, can also be used to mitigate some of the freshwater pressures. Finally, fresh water is unevenly distributed over the planet, and subsequent water shortages will also develop unevenly. Therefore, there will be spatial trade-offs among water-rich and water-poor regions.

12.2.2 Land Use and Biodiversity

The expansion of agricultural production that takes place in all scenarios has potentially severe consequences for biodiversity. Expansion of the total agricultural area decreases the area of forests and grasslands. This reduction leads to a decrease in total vascular plant biodiversity and limits soil formation. (See Chapter 10.) Even though the rate of loss of vascular plant biodiversity in TechnoGarden is slower than in the other scenarios, it still results in approximately 300 vascular plant species being lost each year. Order from Strength provides the worst scenario for terrestrial vascular plant diversity because of the high rate of human population growth and the low agricultural yields (requiring extensive rather than intensive agriculture) resulting from the small transfer of technology from rich to poor countries.

Expansion of agriculture leads immediately to local losses of biodiversity through extirpation of local populations and loss of landscape diversity and, most important, loss of ecosystem services. These losses occur even if species extinctions do not or if extinctions are delayed due to the slow approach to equilibrium.

A number of cascading effects result from the trade-off between land use and biodiversity. Perhaps the most important effects involve the unintentional impairment of supporting services, such as future soil formation, water purification capacity, or the maintenance of species habitat. Conversion of natural forests into croplands will also reduce ecosystem services such as climate regulation and carbon sequestration. The loss of supporting services does not often have immediate consequences. However, the slow degradation of supporting services makes it very hard for future policy-makers to reverse the trend in biodiversity loss. Thus, the heavy emphasis on food production across all scenarios is associated with future reductions of other ecosystem services.

Land use trade-offs may be mitigated by zoning plans that allow multiple uses of land resources within regions and by land use practices that maintain ecosystem services in combination with food production. Policy-makers can also capitalize on the synergistic interactions between land use and the delivery of multiple ecosystem services (forest restoration, for instance, may ''create'' several provisioning, regulating, cultural, and supporting services). Management regimes such as those outlined in the broad-scale policies developed in Global Orchestration may help alleviate land use problems globally, but global policies must also be intertwined with smaller-scale policies, such as those found in Adapting Mosaic, to help avert small-scale land use problems. Development of more-productive crops under TechnoGarden will also alleviate some land use problems.

Nevertheless, land use problems still remain across all scenarios because of the large increase in population. A good approach to managing land to minimize ecosystem service trade-offs will combine the best global policies (including free trade of food resources) with development of smaller-scale policies, such as protected areas and the use of technology that increases food production per square meter of agricultural land. Approaches that integrate continued support of forest areas along with agricultural production (such as shade-grown coffee) minimize land use versus biodiversity trade-offs.

12.3 Trade-offs Illustrated by the Scenarios

In all scenarios, society modifies the supply of a variety of ecosystem services. (See Figure 12.2.) Broadly speaking, under the two ''reactive'' scenarios (Global Orchestration and Order from Strength) the losses are greater than the gains. Even in the ''proactive'' scenarios (Adapting Mosaic and TechnoGarden), however, there are reductions in the supply of ecosystem services in one of the dimensions considered.

In Global Orchestration, society focuses primarily on the provisioning ecosystem services that generate tangible products to improve human well-being. When environmental problems arise, they are dealt with according to the belief that economic growth can always provide resources to substitute for lost ecosystem functions. Proactive management of ecosystem services is not pursued. Under this scenario, society will tend to trade off regulating and supporting services while trying to maximize provisioning ecosystem services.

The trade-off approach for regulating and supporting ecosystem services is slightly different from the approach for cultural ecosystem services. Regulating and supporting services are routinely ignored in trade-off decisions, because in many instances in this scenario, human well-being is very good. For example, increased human and economic well-being leads to urban growth into wetlands and along coastlines, which ultimately causes the diminishment of nutrient cycling and water purification and the elimination of fish habitat within these areas. People in this scenario typically ignore these negative effects until they are a serious problem. In contrast, there is some recognition that cultural ecosystem services or cultural differences are essential to maintain.

At the same time, the emphasis on free trade and global policy causes many cultures to be subsumed into an overall ''global culture.'' For example, even though some aspects of Asian culture are integrated into western business practices, many of the traditional practices, such as religious ceremonies, are eliminated as these cultures strive to become part of the global community. The best example of the emphasis on provisioning ecosystem services in this scenario may be the increased importance of meat in the diet, which results from a general increase in human well-being. The increased production of meat causes extensification of agriculture to provide animal feed. Extensification happens at the cost of land-based biodiversity. This and other similar trade-offs are largely ignored in this scenario, as this change in diet is viewed as a benefit of Global Orchestration policies.

Order from Strength places little value on ecosystem services, because rich and poor countries are both focused on increasing their wealth and power through economic growth. All ecosystem services, but especially those that occur over large spatial or temporal scales, are likely to be traded off, as there are no international mechanisms or incentives to protect them. In rich countries, ecosystems are believed to be robust and therefore are used without restrictions in order to improve human well-being. All that is required is that representative samples are preserved in order to have a ''natural data base'' for developing appropriate technologies to repair or replace them. Provisioning ecosystem services are likely to be favored without considering the impacts on other ecosystem services, as they directly improve human well-being. In poor countries, the conservation of ecosystem services is not considered a priority, thus substantial trade-offs occur among all services. It is assumed that concerns over the delivery of ecosystem services will spontaneously evolve once more-pressing social and economic issues are resolved and that any problems incurred through trade-off decisions will be repairable at a later date.

The lack of value placed on ecosystem services in Order from Strength can perhaps best be illustrated by the exam-

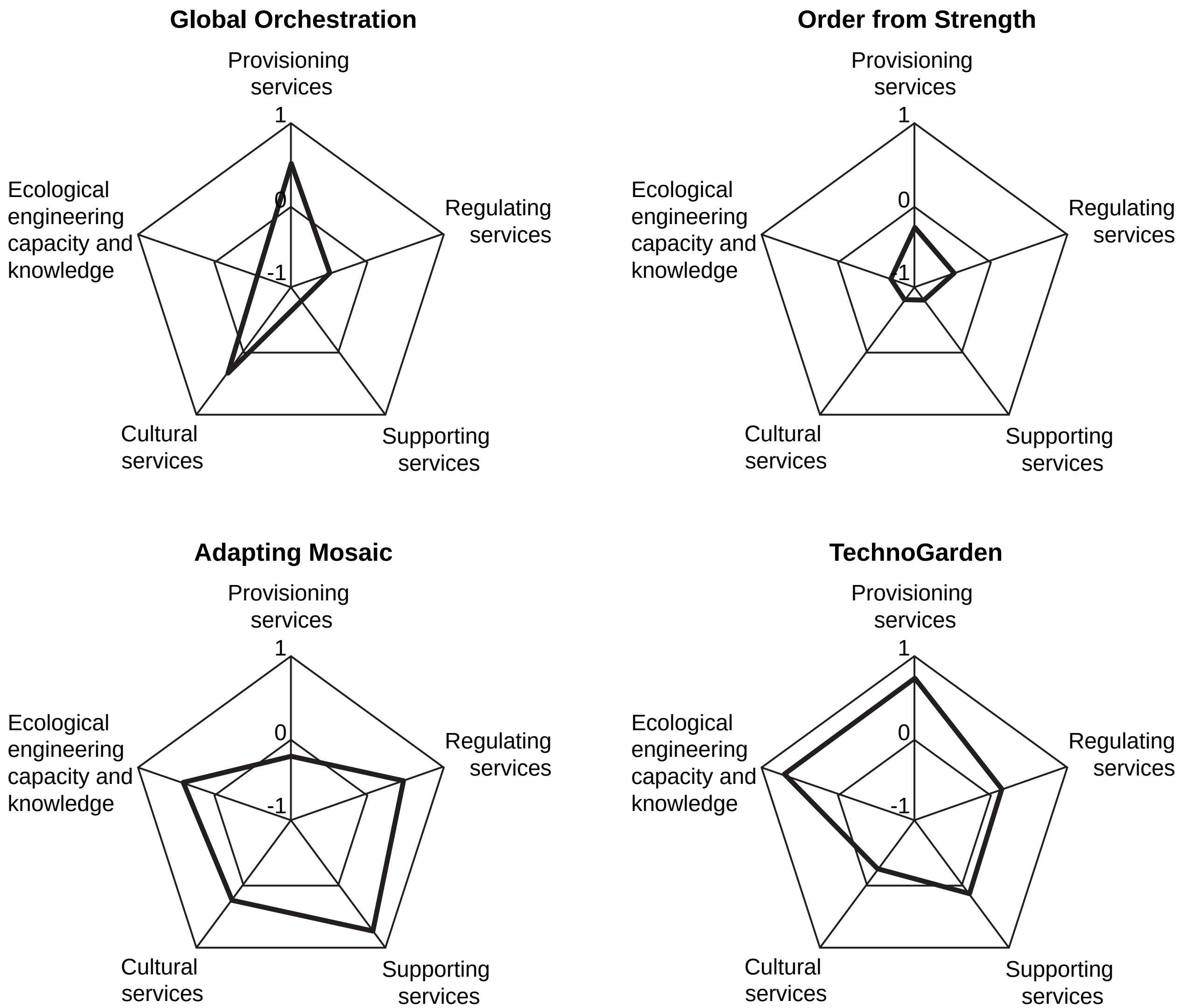

Figure 12.2. Relative Change in Provision of Ecosystem Services in MA Scenarios. Dark lines indicate the state of each Ecosystem Service (ES) at the end of the scenario storyline relative to a starting point of zero. A positive value (between 0 and 1) indicates an increase in the supply of a particular ES. A negative value (between 0 and −1) indicates a decrease in supply. Therefore, as the "stars" increase in size, the overall supply of ES increases, while as they decrease, the overall supply of ES decreases.

ples drawn from marine fisheries and the plight of sub-Saharan Africa. (See Chapter 8.) In Order from Strength, the rich countries use their wealth to control global fisheries while protecting their own stocks. Their emphasis is not on maintaining adequate provisioning resources for human well-being. Instead, they focus on controlling the global market for fisheries to maximize economic gain. Exports of small pelagic fishes are diverted for further production of meat (a luxury food resource in rich countries) instead of being exported as food products to poor countries. Trade-offs at the global scale are nonexistent, as the emphasis is on exploitation for economic gain. In contrast to the rich countries, most of sub-Saharan Africa no longer has food security in 2050, because of the effects of climate modification and population growth in this region. The decision for policy-makers is not about trading off provisioning services for other ecosystem services, but instead is solely focused on maintaining their own food security.

Under Adapting Mosaic, there is no dominant ecosystem service trade-off paradigm, although negative trade-offs tend to decline over time. In the short term, societies are likely to engage in a variety of ecosystem service trade-offs as they experiment with the supply of ecosystem services according to their local needs, especially provisioning services. No single trade-off dominates, since conditions vary globally and societies only focus on their local set of conditions and problems. Over time, local management improves throughout the world. Local institutions and innovations reduce the number and magnitude of negative trade-offs.

The Adapting Mosaic scenario leads to many local management examples that build on previous experiences and deal with each set of trade-offs independently. For example, in the Euphrates-Tigris river (see Chapter 8), the initial trade-off decisions provide more provisioning services (cotton production) at the expense of supporting and regulating services (soil formation, saline control on the land). However, working within the area, managers learn how to use the Adapting Mosaic of conserved areas to eventually craft solutions that provide for ''win-win'' interactions in provisioning, regulating, and supporting ecosystem services. Similarly, malaria control in Africa (see Chapter 8) involves the trade-off of a regulating ecosystem service (disease control) with a provisioning service (fresh water). Through the use of adaptive management on a fairly small scale, however, managers are able to craft solutions that produce ''win-win'' solutions that provide both fresh water and malaria control.

TechnoGarden assigns high value to ecosystem services, but mainly from a human-use perspective. This means that cultural ecosystem services are more likely to be traded off and lost than other types of services. Initially, there is great interest in the variety of provisioning, regulating, and supporting ecosystem services as models for possible technological developments, but as key societal ecosystem services are identified and replaced by technological equivalents, society becomes more likely to trade off any existing ecosystem services for their engineered alternatives. In the short term, society will predominantly trade off cultural ecosystem services for other types of services; in the long term, all types of services may be traded off as key ecosystem services are identified and technologically optimized.

The emphasis on technological fixes leads to the rapid urbanization of many parts of the globe, especially in Asia. As urban areas grow, traditional cultural resources such as temples and religious sanctuaries are traded off for urban areas. This is not a long-term solution, however, as there still is a need for cultural services, and many are ''reinvented'': the rebirth of Japanese urban gardens, for instance, or the creation of salmon festivals in the U.S. Pacific Northwest or the Gojiro festivals in Japan.

One of the most important conclusions from all scenarios is that the total pressure on ecosystem services worldwide will increase. Some of this is a consequence of the projected human population growth used in these scenarios. Even in cases such as TechnoGarden and Adapting Mosaic (which attempt to mitigate some of these environmental pressures), increases in provisioning ecosystem services will be traded off against supporting and regulating services. There is perhaps no more compelling example than the combined synergistic effect of greater use of greenhouse gases (through increased human population and a greater reliance on fossil fuels technology) and the decline in carbon sequestration that has resulted from the conversion of forested areas into agriculture. Thus, the ability of the biosphere to regulate climate change—even with the technological fixes expected in TechnoGarden or the localized controls of Adapting Mosaic—will not be easily restored, as the regulating and supporting services provided by forests are traded off by the additional expansion of agriculture, a provisioning service.

We also examined the trade-offs and synergisms among ecosystem services that might develop as governments work to achieve the Millennium Development Goals adopted at the UN General Assembly in September 2000. The eight goals are to eradicate extreme poverty and hunger; achieve universal primary education; promote gender equality and empower women; reduce child mortality; improve maternal health; combat HIV/AIDS, malaria, and other diseases; ensure environmental sustainability; and develop a Global Partnership for Development (UNDP 2003).

The scenarios offer a number of insightful illustrations of the ways in which ecosystem service trade-offs may affect the ability of governments to reach the MDGs. Let us consider the first goal: the eradication of extreme poverty and hunger. Each scenario indicates a different likelihood that this goal will be met. For example, Global Orchestration has the greatest reduction in poverty and hunger as a result of improvement in the delivery of provisioning services. In contrast, hunger and poverty regimes continue to exhibit strong rich-poor divides under Order from Strength, although this disparity is lessened among northern countries. Achieving poverty alleviation in the short term may also be accompanied by long-term costs, such as narrowing the genetic base of crops or increasing nutrient input to freshwater systems from fertilizers and pesticides.

The drive to eradicate extreme hunger and poverty has ramifications for biodiversity. It also demands actions that will carry important implications for the attainment of the other MDG. Analysis of the scenarios shows that one of the major trade-offs common to all scenarios is between land use and biodiversity (as described earlier in this chapter). Although there are certainly ways to mitigate the impacts of this trade-off (perhaps through the innovations found in TechnoGarden or the emphasis on more thorough environmental accounting in Global Orchestration), policy-makers will face choices that may favor the first Millennium Development Goal at the expense of biodiversity.

Another MDG is to ensure environmental sustainability. All scenarios indicate that the volume of polluted water will increase as a result of the projected increase in agricultural production. Further increases in the use of water for food production also indicate that there will be a decrease in freshwater biodiversity. Policy-makers will be forced to examine the trade-offs among the two goals (eradicating extreme poverty and hunger and ensuring environmental sustainability) and, where possible, to develop policies that produce ''win-win'' outcomes. This will be a complex process that draws heavily on the past experiences of natural resource managers, as illustrated in the case studies and the scenarios. Whether it is realistic to expect that the Millennium Development Goals can be reached without a significant loss of biodiversity remains to be seen.

12.4 Interactions among Ecosystem Services in Selected Case Studies

One way to understand the consequences of ecosystem services decisions is to examine the outcomes of past management activities. The following examples illustrate some of the dilemmas and trade-offs that society must face when deciding to enhance one ecosystem service without fully understanding the impacts on other services. The order of this presentation is arbitrary and does not reflect any attribute of the ecosystem services involved, the region, or anything else. Our goal is to provide a series of examples of the implications of human actions directed at modifying the outputs of one or more ecosystem services. We did not attempt to be comprehensive, just illustrative.

12.4.1 Vulture Declines in India

The recent sudden decline of Gyps vultures in eastern India provides a compelling example of how species declines can cause declines in provision of many ecosystem services, illuminating unexpected synergisms among species and socio-ecological processes. Vultures play an important role as natural garbage collectors in many parts of India. In particular, vultures help to dispose of cattle carcasses in areas where beef eating is forbidden. In Amritsar, center of the Parsi religion, they also help remove human corpses from traditional sites of "laying to rest."

In the last few years, vulture numbers suddenly declined, with consequences that cascaded throughout the region. Since there are too few vultures to clean the corpses, the Parsi are no longer able to lay their dead to rest without causing a health hazard. Instead, the dead are stored until a future time. But the less obvious consequences are leading to even more dramatic effects. Carcasses of cattle are transported to areas on the edge of towns and villages. These areas are now increasingly dangerous to visit because vultures do not rapidly remove the meat from carcasses, tempting other carnivores to the area. Feral dog populations have increased as a result of the lower competition with vultures for meat. Growing dog populations are likely to cause an increase in rabies risk, dramatically heightening the consequences of being attacked by a dog.

Vulture declines have recently been linked to the use of the veterinary drug diclofenac (Oaks et al. 2004). Thus, in this example, attempts to improve the health of domestic animals had a series of cascading, unanticipated, and unknown effects on many other services, even to the point of possibly having a negative effect on human disease in the area. Depending on whether the impact of diclofenac proves to be reversible or irreversible, this trade-off could be classified as Type A or E, as described in Figure 12.1. That is, this trade-off is local, rapid, and of unknown reversibility.

12.4.2 Lakeshore Development in the Northern United States

Property values surrounding lakes in northern Wisconsin in the United States are strongly linked to the development patterns around the lake. During the last 30 years, there has been a substantial increase in the development and building on lake shores (Peterson et al. 2003) that has resulted in the creation of a "lake community" on many lakes. The initial conversion of these lakes from undeveloped to developed shorelines resulted in an increase in property values around these waters. Although development was accompanied by an initial increase in cultural ecosystem services, changes in shoreline vegetation resulted in increased sedimentation (soil loss; soil provides a supporting ecosystem service), a reduction of the amount of habitat (a supporting ecosystem service) available for fishes (Christensen et al. 1996), and a decrease in fish growth rates (Schindler et al. 2000).

Although zoning regulations can help to control shoreline development, lake communities are often resistant to zoning and control, even though there is evidence that zoning results in even higher increases in property value (Spaltro and Provencher 2001). In addition, shoreline developments often lead to increases in primary production due to increased fertilizer use and sedimentation from runoff. The consequence is a decrease in water quality (regulating ecosystem service) and subsequent reduction in the aesthetic quality of the lake (cultural ecosystem service).

Resistance to zoning and government regulation by property owners in this area led to overdevelopment and the environmental impacts just discussed. It remains to be seen whether the long-term cumulative environmental impact will negatively affect property values. Several types of trade-offs are involved here. For example, the reduction of fish habitat is probably irreversible, local, and rapid (Type E), while decreases in water quality and aesthetic value of lakes may be reversible (with successful enforcement of regulations on fertilizer use), large-scale, and long-term (Type D).

12.4.3 Fisheries and Tourism in the Caribbean: Jamaica and Bonaire

Many ecosystem services are provided by the Caribbean Sea. Two of the most prized are fisheries and recreation. The Caribbean attracts about 57% of scuba diving tours worldwide. In the 1950s, 1960s, and 1970s, Jamaica was the prime dive location, and hard corals covered as much as 90% of shallow coastal areas (Goreau 1959). By the late 1960s, chronic overfishing had reduced fish biomass by about 80% compared with the previous decade (Munro 1969). Then, in the early 1980s, two extreme events hit Jamaican coral reefs, causing their collapse. In 1980, Hurricane Allen broke many large elkhorn and staghorn corals into pieces (Woodley et al. 1981). In 1983, an unidentified disease spread throughout the Caribbean and killed 99% of black-spined sea urchins (*Diadema antillarum*), the primary grazer of algae on the reefs (Lessios 1988). Without the ecosystem services provided by grazing fish or sea urchins, fleshy macro-algae came to dominate coral reefs (more than 90% cover) in just two years (Hughes 1994). The lucrative dive tourism industry in Jamaica declined.

When the sea urchin mass mortality occurred throughout the region, most sites suffered algal overgrowth, but a few sites did not. Sites like Bonaire, with abundant grazing fish, had no reported algal overgrowth. In Bonaire, the Reef Environmental Educational Foundation has recently generated statistics from about 60,000 coral reef fish surveys, which rate seven dive sites in Bonaire among the top 10 worldwide for fish species richness, with over 300 species (REEF 2003). Bonaire banned spear fishing from its reefs in 1971. In 1979, the Bonaire Marine Park was created to preserve for scuba divers the entire area surrounding the island, from the shoreline to 60m depth. In 1992, active management of the park started with the introduction of mandatory permits for divers, bringing in about $170,000 a year to support protected area management. Economic activities (dive operators, hotels, etc.) connected with the park attract about 10,000 people annually, valued at over $23 million per year. In contrast, the cost of park management is under $1 million per annum.

Thus, protecting the fish for the regulating ecosystem service they provide as algal grazers and for their aesthetic attraction to tourists yielded a positive financial return in the long term. In this case, regulating provision of one service (the fishery) maintained resilience in the system and led to a long-term gain in provision of recreation as well as a stable, long-term fishery. These synergistic interactions among ecosystem services allow for the simultaneous enhancement of the supply of more than one ecosystem service.

12.4.4 Fertilizer Use in the United States

Intensive agriculture within the United States has resulted in massive soil loss (a decrease in a supporting service) throughout the Mississippi drainage region (Malakoff 1998). The initial conversion of land in this area from prairie and grassland to agriculture was motivated by an interest in increasing food production (a provisioning service). To maintain high levels of crop output in spite of topsoil erosion, farmers have maintained soil fertility through the addition of either natural (manure) or chemical fertilizers.

The effects of the high level of artificial fertilization have also resulted in massive changes in downstream areas: many small-scale changes by individual farmers on their own fields have resulted in the creation of a hypoxic zone (a ''dead zone'') in the Gulf of Mexico. (See Chapter 8.) This zone of low oxygen has resulted in declines in the shrimp fishery as well as in other local fisheries in the Gulf region (Malakoff 1998). In this case, attempts to maintain and increase the provision of one service, food, have caused substantial declines in many ecosystem services in another location. The effects of this trade-off are felt over a large spatial scale and are likely to last for a long time. Whether they are reversible or not remains to be seen. The trade-off can therefore be classified as Type D or H.

12.4.5 Mine Effluent Remediation by Natural Wetlands on the Kafue River, Zambia

An example from Zambia demonstrates a trade-off in which protection of an extensive, unique ecosystem is achieved through the degradation of smaller, upstream wetland systems (von der Heyden and New in press-a). The Kafue River originates along the watershed between Zambia and the Democratic Republic of the Congo 100 kilometers northeast of the industrialized Copperbelt mining region. It is the dominant source of water and food for various urban and rural settlements and enterprises. Although the river only drains 20% of Zambia's surface area, it is the principal water source for all of the country's major towns (Mutale and Mondoka 1996). Wetlands, locally called *dambos,* are apparent throughout the Copperbelt Province, where they occur primarily as headwater features forming the source of the Kafue River.

Commercial mining on the Copperbelt began in the 1920s, and since then the region has been characterized by one of the highest densities of large-scale mines in the world. Mining-related contamination of the Copperbelt's water resources has been a matter of great concern over the past decades (Pettersson and Ingri 2001). Since many Copperbelt mines and their related infrastructure are located on or near the catchment's rim, effluent originating from these operations follows the natural drainage path, first entering the dambo wetlands before discharging into larger waterways and ultimately the Kafue River (Limpitlaw 2002). Although wetlands throughout the Copperbelt have been affected and degraded as a result of the discharge of mine effluent, these systems have given a considerable level of protection to the downstream ecosystem through the filtration, retention, and remediation of effluent contaminants within the wetland sediment and flora (von der Heyden and New in press-b, in press-c).

While the wetland systems demonstrate great efficiency in protecting downstream environments from mine-related pollutants, natural wetlands are known to be fragile ecosystems that are extremely valuable to local resource users and are a key component of the regional ecosystem. It is uncertain if the wetlands are able to provide their regulating ecosystem services indefinitely or at a constant level. Further understanding of the complexity of factors affecting the impact, capacity, and alternatives to the use of natural wetlands in mine effluent remediation is necessary to assess comprehensively the role of the wetlands in the management of the Copperbelt environment. Perhaps irreversibly, ecosystem services provided by wetlands have been traded off for the long term, over large spatial scales. Thus this trade-off can be classified as Type H.

12.4.6 No-take Zones in St. Lucia

As fisheries worldwide continue to decline (FAO 1996; Jackson et al. 2001; Myers and Worm 2003; Roberts 2002), there has been an increasing interest in fishery exclusion zones, both to allow for the recovery of targeted species and as a mechanism to increase the catch outside of protected areas. Recent research suggests that these objectives can be successfully achieved by the designation of no-take marine reserves (Gell and Roberts 2003a).

For example, the Soufrière Marine Management Area, created in 1995 along 11 kilometers of the coast of St. Lucia in the Caribbean, includes five small marine reserves alternating with areas where fishing is allowed. Roughly 35% of the fishing grounds in this area has been set aside and protected. The initial cost of restricting access to fishers in about a third of the available area (a decline in a provisioning ecosystem service) has been easily compensated for by the benefits. As may be expected, fish biomass inside the reserves tripled in just four years, but, more important, biomass in the fished areas doubled during the same period and remained stable thereafter (Roberts et al. 2001). In less than the typical term of an elected governmental official, the fishery recovered and landings increased. There is growing evidence from around the world supporting marine reserves and fishery closures as an effective tool for managing fish, one of the most important provisioning ecosystem services (Gell and Roberts 2003b). Wise local management of fisheries averted a negative impact, possibly for the long term. Therefore this is an example of a Type B interaction.

12.4.7 Lobster Fishing in Maine

Lobster fishing in the northeastern United States has important social and economic consequences for many of the coastal communities in this region. Perhaps nowhere is it more important than in the state of Maine, which harvests the majority of lobster produced in the country (Acheson and Steneck 1997). Since 1870, this fishery has experienced a period of bust followed by a fairly extended period of boom in the numbers of lobster produced. A combination of formal state-based and informal social regulations set and enforced by territorial harbor cooperatives has contributed to the expansion and continued success of the lobster fishery, even as other fisheries in the same area have failed (Acheson et al. 1998; Jackson et al. 2001).

The lobster fishery provides important provisioning services such as food and economic well-being for communities. The development of harbor cooperatives for social enforcement of regulations also provides members and communities with a sense of identity, which is important for social reinforcement of informal regulations on the fishery (Acheson et al. 1998). The strong bonds created within the harbor cooperatives help limit the total effort within the fishery (resulting in a short-term economic cost), assuring that harvest is limited and the lobster fishery is preserved for the long term (Acheson et al. 1998).

The cultural services provided by the lobster cooperatives may have also had synergistic effects, because one of the contributing factors to the current lobster boom is an increased conservation attitude among lobster fishers (Acheson and Steneck 1997; Acheson et al. 1998). Formation of lobster cooperatives provided the social fabric and peer pressure necessary for lobster fisheries within to adhere to a conservation ethic. This "win-win" outcome in a fairly small-scale system was a product of synergistic interactions among ecosystem services and it helped play a part in the lobster boom and maintain the cultural identity of the lobster communities.

12.4.8 Water Quality and Biological Invaders in the U.S. Laurentian Great Lakes

Beginning about 1870, a set of connected canals was opened in Chicago, Illinois, that reversed the flow of the Chicago River. The purpose of the engineering project was to flush waste from the burgeoning number of human households and slaughterhouses away from Lake Michigan, the drinking water supply for the growing city. The Chicago River, which had naturally flowed into Lake Michigan, was thereby linked via the Chicago Ship and Sanitary Canal to the Mississippi River drainage; over time this became an important conduit for commercial and recreational navigation, as well as a huge open sewer. Because the canal was filled largely with untreated sewage and animal waste, dissolved oxygen concentrations were too low for most organisms to survive for many miles downstream in the Des Plaines and Illinois rivers. This caused a complete loss of riverine fisheries until the 1970s, when Clean Water Act regulations made the waterway habitable again for fish and other organisms.

Paradoxically, the consequence of improved water quality in the last three decades has been a surge in invasive species moving in both directions in the canal. The best documented example is the rapid spread of zebra mussels (*Dreissena polymorpha*). From its initial site of introduction in the Great Lakes about 1986, zebra mussel larvae were transported down the canal into the Illinois and Mississippi rivers, all the way to New Orleans (just north of the Gulf of Mexico) in about four years (Stoeckel et al. 1997). The consequence of zebra mussel spread within the Great Lakes has been $100 million in annual costs to the power industry and other users, extirpation of native clams in Lake St. Clair, and large changes in energy flow and ecosystem function (Lodge 2001). Other nonindigenous species in the Great Lakes—two fish, for example, the round goby and the Eurasian river ruffe (*Gymnocephalus cernuus*)—are also nearing the canals and could join the zebra mussel in its southward migration. Other species that have had large impacts elsewhere—two Asian carp species are of special concern—are migrating northward and nearing Lake Michigan (Stokstad 2003).

12.4.9 Flood Control by the Three Gorges Dam in China

The construction of the Three Gorges Dam in China is an effort to provide a technological substitution for the ecosystem services of flood control while also producing electricity through hydropower. Flood control is important for the well-being of the millions of people, mostly rice farmers, who live on the floodplain of the Yangtze. Sedimentation from the Tibetan plateau has raised the height of the Yangtze channel to the point where it now sits several meters above its floodplain. Once the Three Gorges Dam is constructed, it is anticipated that large floods on the Yangtze will be controllable.

Construction of the dam will have other effects as well, however: Once the dam is full, levels of schistosomiasis near Chongqing, at the north end of the impoundment, are predicted to rise dramatically as a consequence of the decreased water speed. The capacity of the Yangtze to remove wastes, including industrial effluent and sewage, will also be significantly reduced. Water quality within the long, narrow impounded area is likely to decline. The reservoir that resulted from the construction of the Three Gorges Dam has necessitated the relocation of around 2 million people and caused flooding of numerous villages and historical monuments.

The decision to build the dam is in part a consequence of earlier decisions that encouraged people to settle in the wetland areas that would formerly have provided flood control services. Some of the ecosystem services provided by the Yangtze that will be lost, such as disease regulation, food production, and waste removal, have been assigned a relatively low priority compared with energy and flood control, which will be gained. Interestingly, the communities negatively affected by schistosomiasis (upstream) will be different from those that benefit from flood control (downstream).

As shown in this case, it is not uncommon that management of ecosystem services may result in an inequitable distribution of the benefits and costs of management actions. This example also shows that when a management decision is focused on a small subset of ecosystem services (flood control and electricity production, in this case), the impact of the decision on interrelated secondary services may be largely ignored. This is an example of a Type H trade-off: irreversible, large-scale, and long-term.

12.4.10 Dryland Salinization in Australia

Dryland salinization has been a major issue facing farmers in Australia since the 1930s. It was not until the late 1980s and early 1990s, however, that the problem moved from being individual to collective (Anderies et al. 2001; Greiner and Cacho 2001; Briggs and Taws 2003). To increase agricultural production (a provisioning service), many farmers cleared the original woody vegetation and replaced it with pastures and crops (Schofield 1992; Farrington and Salama 1996). The natural tree landscape of Australia had provided an important but undervalued regulating service by maintaining the groundwater at low enough levels that salts were not carried upwards through the soil. Once the woody vegetation was removed, the groundwater table moved toward the surface, bringing salt into the surface soils. As the salt content in soils increases, lands become unusable for traditional agriculture (Anderies et al. 2001; Greiner and Cacho 2001; Briggs and Taws 2003).

Dryland salinization motivated the development of the Hunter river salinity trading scheme (www.epa.nsw.gov.au/licensing/hrsts/index.html) and a political push to move toward salt-trading schemes that start with the development of salinity targets (www.mdbc.gov.au/naturalresources/salinity/factsheets/fsa1002_101.html). Ecological restoration efforts include planting trees in plots contiguous to fields to recover the ecosystem services provided by native vegetation (Schofield 1992; Farrington and Salama 1996). The total amount of land available for grazing decreases since trees take up some of the space, but tree plots help maintain the water table low enough to avoid salinization (Anderies et al. 2001; Briggs and Taws 2003). In areas of the Murray River catchment, the establishment of salt quota allocation systems is also necessary to assure that salt levels in the drinking water supply for Adelaide remain low (Anderies et al. 2001). Dryland salinization therefore has both local and distant effects, illustrating the spatial segregation of trade-offs among ecosystem services.

12.5 Characteristics of Trade-offs in the Scenarios and Case Studies

One way to look at the implications of policy-makers' actions on the delivery of ecosystem services is to ask which ecosystem service is traded off (explicitly or implicitly) when another service is selected as a target of a policy prescription. Though trade-offs may lead to the ''sacrifice'' of one service for another, this is not always so. In some cases, non-target ecosystem services may be enhanced, leading to a synergistic increase in the services provided. Analysis of results from the case studies allow for the identification of policies that have led to ''win-win,'' ''win-lose,'' and ''lose-lose'' situations, according to whether the policy recommendation resulted in a positive response in both the targeted and other ecosystem services, a negative and a positive response, or two negative responses. (See Table 12.1.)

We find examples of all three types of trade-off. Two cases stand out as clear ''win-win'' situations. Lobster fishing in the northeastern United States and no-take areas and fishery production in Saint Lucia show how short-term losses in catch due to the policies implemented led to long-term increases in production. Human well-being and fishery production both increased by enlightened management. In contrast, the remediation by natural wetlands on the Kafue River in Zambia is a candidate for a ''win-lose'' case: the quality of highland wetlands was ''sacrificed'' by mining effluents, though the wetlands still continue to provide this regulating ecosystem services. (It remains unclear if they can maintain the service at the same level or do it in perpetuity.) In addition, society can benefit from the income generated from mining, and the quality of water is maintained.

Identification of common characteristics found among trade-off decisions will allow policy-makers to develop better-informed decisions about the choices that they face. Understanding typical trade-off patterns associated with

Table 12.1. Types of Ecosystem Service Trade-offs in Case Studies. The plus and minus signs next to the numbers for each case study indicate positive and negative impacts, respectively, over the ecosystem service or services traded off. Two plus or minus signs indicate more than one service traded off in that category. Two signs separated by a slash indicate short-term/long-term differences in the trade-off or spatially segregated costs and benefits. Key to the case studies (see section 12.4 for their full names): 1: vulture declines in India, 2: value of lakeside property in the United States, 3: fisheries and tourism in the Caribbean, 4: fertilizer use in the United States, 5: remediation by natural wetlands on the Kafue River in Zambia, 6: no-take areas and fishery production in Saint Lucia, 7: lobster fishing in the northeastern United States, 8: Great Lakes of the United States, 9:Three Gorges Dam in China, and 10: dryland salinization in Australia.

Ecosystem Service Traded off	Ecosystem Service Targeted			
	Provisioning	Regulating	Cultural	Supporting
Provisioning	6(−/+), 7(−/+)	8(− −), 9(+)	2(−)	
Regulating	1(− −), 3(−), 5(−/+), 10(−)	8(− −), 9(− −)	2(−)	
Cultural	7(+)	1(−)	2(−)	
Supporting	4(−)	8(−)	2(−)	4(− −)

ecosystem management decisions may help managers comprehend the implications of their choices, even when they cannot predict the secondary services that will be affected. Common characteristics arise from analyses of the trade-offs found across all four scenarios and can be illustrated by examples drawn from real-world decision-making. In this section we summarize some of the main issues that must be considered when making decisions about ecosystem service trade-offs.

12.5.1 Unknown and Unanticipated Trade-offs

In all four scenarios and in our real-world case study examples, numerous trade-offs exist that are unknown and unanticipated. These may not manifest themselves until long after the initial decisions are made, even though they are already affecting the mix of ecosystem services provided. Illustrating such examples from within the scenario results themselves is difficult, because if the unknown and unanticipated trade-offs were known, they could be planned for. Instead the scenarios present many surprises (based on known interactions) that, in the real world, could be a result of unknown and unanticipated events. For example, in TechnoGarden, allergies to the pollen of genetically modified organisms develop, and massive exotic algal blooms occur as a result of failed water-supply manipulations. These surprises are a result of management trade-off decisions that result in unpredictable changes, forcing managers to make additional, unanticipated trade-off decisions.

While the previous example comes from the scenarios, the case studies also clearly show that unanticipated trade-offs are common and indicate that we can expect more unexpected trade-offs and synergies in the future. For example, vulture declines in India are remarkable in demonstrating how a change in the abundance of one species can have unexpected consequences over something as seemingly unconnected as the presence of rabies in dogs. Similarly, in the Great Lakes ecosystem, the efforts to increase waste removal and, later, to improve water quality in the waste canal led to a subsequent increase in non-native species, which has contributed to the long-term decline of biodiversity within the Great Lakes ecosystem.

Even the best models, classification schemes, or processes used to understand the trade-offs inherent in management decisions will not be able to anticipate all the effects of these decisions. Ultimately, there will always be some unanticipated effects of management decisions. Yet there are management techniques that can be used to mitigate the impact of unanticipated trade-offs. Management designed to maintain or improve resilience may help mitigate the impact of unanticipated effects, as seen in the Bonaire example. Resilience can be incorporated into ecosystems, for example, by creating redundant approaches to providing similar ecosystem services within each ecosystem. Development of a protected areas network that has multiple protected areas within a broader ecosystem would be one example of incorporating redundancy into ecosystem management plans. The use of adaptive management, or learning by doing, allows lessons learned from unanticipated effects to be applied to future decisions.

12.5.2 Choice of Ecosystem Service Trade-offs

Policy-makers are often forced to choose some ecosystem services over others. Across all four scenarios, trade-off decisions show preference for provisioning, regulating, cultural and supporting services, in that order. In all instances the increase in population growth, a major assumption of the scenarios, forces trade-offs that tend to favor provisioning and, to some extent, regulating ecosystem services. This is not surprising, as management choices tend to increase the supply of services that are perceived by society as more important—provisioning and regulating services—and thus do not fully value trade-offs of cultural and supporting services. In addition, supporting services are more likely to be ''taken for granted.'' Because supporting and regulating services contribute to the ability of ecosystems to provide provisioning in the future, these decisions may be seriously undermining the future of provisioning ecosystem services and human well-being.

Real-world examples support the contention that managers must make trade-offs that explicitly or implicitly lead to preferences among ecosystem services. For example, the Three Gorges Dam in China is expected mainly to prevent floods (regulating ecosystem service) and will also positively affect electricity and food production (provisioning ecosystem services), but will negatively affect disease regulation and waste removal (regulating ecosystem services) and biodiversity. Perhaps the most telling example is that of the value of lakeshore property in the United States: developments targeting the cultural ecosystem services provided by owning a home near the water create negative impacts on other provisioning, regulating, cultural, and supporting ecosystem services, which in turn undercut the cultural service that they initially sought to optimize.

The recognition that managers rank ecosystem services in specific sequences allows a better understanding of how trade-off choices are made. Managers can then acknowledge that their decisions have ramifications on the supply of other ecosystem services and provide support for examining all aspects of each trade-off decision.

12.5.3 Slowly Changing Factors

The slowly changing factors that underlie supporting and regulating services are often ignored by policy-makers and not actively pursued by policy processes. Because supporting services often depend on slowly changing factors such as soil fertility, groundwater levels, or soil formation, they may not generally be perceived to be responsive to policy intervention. Slowly changing factors are rarely quantified and may be difficult to monitor. However, as discussed in Chapter 3, it is often these slowly changing variables that lead to unanticipated changes in ecosystem services.

In many instances, society chooses to trade off supporting or regulating services in favor of short-term provisioning ecosystem services. The case study examples about fertilizer use in the United States and mine effluent in Zambia illustrate this type of trade-off. Inattentiveness to supporting and regulating services can lead to a loss of resilience, leaving socioecological systems more vulnerable to surprises in delivery of provisioning services. Surprise, which is often linked to the misunderstanding or non-identification of the slow variables that regulate ecosystem services, is a common part of ecosystem management (Gunderson and Holling 2002).

Across all scenarios, such surprises or unexpected consequences of ecosystem management lead to a litany of additional trade-offs that society must make to ensure maintenance of ecosystem services. That is, short-term choices for human well-being can be derailed by surprises, ultimately leading to negative impacts on long-term human well-being. Addressing the negative impacts after the fact may be more costly than effectively managing the slowly changing variables to avoid problems in the first place. People in the Global Orchestration scenario focus on short-term availability of provisioning services and generally ignore slowly changing variables, with the idea that they will be able to address the impacts of the trade-off on other services after people have enough provisioning services. In this sense, the scenarios indicate the importance of recognizing the existence of delays. Many ecosystem problems only become apparent after a long time period. The long-term implications of decisions means that in many cases management regimes are only put in place after meaningful change can happen.

The results of trade-off decisions in the scenarios and case studies can be used to help understand the implication of slowly changing factors. Recognizing the importance of slowly changing factors and their effects on the long-term delivery of ecosystem services will help us develop more successful management plans. For example, land use plans in agricultural areas that recognize that high fertilizer use will ultimately result in lower water quality will be more successful in the long-term provisioning of clean fresh water than plans that do not. Such management plans might limit the impacts of fertilizer through reduced use, development of buffers, or other technology to assure water quality in the future.

12.5.4 Temporal Trade-offs

Managers must clearly identify trade-offs to allow policy-makers to understand the long-term effects of preferring one ecosystem service over another. Many decisions are made to maintain provisioning services in the present, often at the expense of provisioning services in the future. The decision to provision now versus provision later is especially pervasive in the Order from Strength scenario. Long-term decision planning is very hard to do, because many managers are rewarded for short-term success. Achieving short-term success may mean forgoing opportunity for future rewards. However, long-term rewards are characteristic of some real-world examples, such as no-take zones in St. Lucia and lobster fishing in Maine. In these two fishery examples, a short-term loss caused by the implementation of fishing restrictions was compensated by a long-term increase in production as stocks recovered. Limitation of ''free access'' to these resources was also fundamental.

Formal acknowledgement that trade-off decisions operate across time will help managers and policy-makers understand the importance of thinking about ecosystem services beyond the immediate need. Development of management regimes for protection of ecosystem services will have to incorporate an understanding of the time scales at which each trade-off occurs (at least the known ones) and ways to assure there is balance between short- and long-term needs from ecosystem services. Recognizing and planning beyond the traditional short-term time frames common in traditional resource management will help build potential for success stories like the St. Lucia case study. Management schemes that do not recognize the long-term effects of trade-off decisions will not be as successful as those that do. Incentives that cause a decline in future discount rates and thus increase the willingness of people to invest for the long term will give managers tools that help mitigate the effect of short- versus long-term trade-off effects.

12.5.5 Spatial Trade-offs

Trade-offs are also often made spatially. Management decisions can have impacts in areas far removed from where the initial trade-off decision occurs. This is especially relevant for the trade-off decisions that are made within the Order from Strength scenario. Decisions made in that scenario rarely take into account the possible implications outside political borders. Lack of accounting for spatial considerations when making trade-off decisions within the Order from Strength scenario creates further pressure on resources in regions where resources are scarce. The Global Orchestration scenario, in contrast, has mechanisms for coping with trade-offs, which allow accounting for decisions outside traditional trade-off boundaries. In many instances this means that there can be more equitable resource distribution cross political borders. In contrast to decisions made about temporal resources, many policy-makers facing ecosystem service trade-off decisions do not account for the spatial effects of those decisions or for the kinds of landscape- and ecosystem-wide effects that are discussed in Chapter 3.

Case studies also portray the dilemmas associated with decision-making at multiple spatial scales. For example, consider the case of dryland salinization in Australia. Each farmer, caring only for his land, removed woody vegetation in order to have more space for crops and pasture. Unfortunately, the actions of many individual farmers added up to the serious ecological problem of dryland salinization. Ecological restoration efforts focused on planting trees affect the water table relatively quickly at the local level, but the establishment of a successful salt-allocation system for an entire watershed, as is needed to assure water quality for the city of Adelaide, is much harder to implement. Similarly, excessive nutrient use on farms in the Mississippi River watershed, which increases food production, is having a negative impact on ecosystem services far downstream in the Gulf of Mexico.

Many managers recognize the need to consider the effects of trade-off decisions outside of traditional geopolitical boundaries. However, there are few incentives for managers to make decisions for the greater good at the cost of local or small-scale well-being. The dilemma faced by policy-makers is that successful management of ecosystem service tends to occur at fairly small spatial scales, while trade-offs that occur at larger scales ultimately affect even the smallest-scale ecosystem. Incentives that encourage policy-makers to bring expert experience of small-scale ''win-win'' solutions to large-scale problems may help policy-makers think broadly about decisions. Further, development of models that allow small-scale systems to be applied to large-scale problems will ensure that these experiences can be used for the greater good.

12.6 Conclusions

Trade-offs are a matter of societal choice. The lessons gained from scenarios and the examination of case studies, including the explicit recognition of trade-offs and their importance for the long-term sustainability of ecosystem services, will help policy-makers to gain a better understanding of the choices that they face and their consequences. In this section, we summarize some of the major implications of the material in this chapter.

12.6.1 Cautions about Quantitative Models

We need to be cautious about using quantitative models, including the ones in the MA, because these rarely represent trade-offs with accuracy. As in any modeling exercise, the qualitative and quantitative results from the scenarios are built on a series of assumptions. For example, there are assumptions regarding fertility, mortality, and migration of humans and the qualitative and quantitative aspects of economic growth. (See Chapter 9.) These assumptions are designed to match the scenario storylines and drive the results of the modeling. The models, in turn, are able to project outcomes over a relatively small array of ecosystem services (see Chapter 9), allowing us to develop an expectation of the conditions of the world under the different scenarios, using a sample of the services provided by ecosystems to humanity. At this point, one could ask: Are trade-offs adequately described by the storylines or the models? Are there any important trade-offs left out? What does our collection of case studies tell us about the importance of trade-offs that are missed by the storylines or the models?

Though the answers to these questions might appear obvious, as nobody doubts that models are only a simplified version of reality, their consequences are very important. Let us consider initially the last two questions and return to the first one later. A quick glance at Table 9.1 in Chapter 9 highlights the biases in the quantitative scenario analysis: there is a strong dominance of provisioning and regulating ecosystem services. Interestingly, this lines up perfectly with our case studies: provisioning and regulating ecosystem services are targeted more often than other ecosystem services. Certainly not by accident, the models focus on the ecosystem services that appear to be perceived by society as more important (driving research agendas and funding) and give less attention to cultural and supporting services.

There are two consequences of this bias. First, cultural and supporting services are essentially left out of the quantitative modeling exercise altogether. We know from the scenario assumptions that Order from Strength and TechnoGarden are more likely to trade off cultural ecosystem services over others, but since we are unable to compare these services in the scenarios quantitatively, the relative gain or loss of cultural ecosystem services cannot be formally expressed. The challenge is probably greater for supporting ecosystem services, as ''those are necessary for the production of all other ecosystem services'' (MA 2003). The fact that existing models do not consider these services is a limitation. Not considering supporting services almost guarantees that we will face surprises and sudden shifts in provisioning services in the future. Since we know that addressing these after they are a problem is generally more costly and time-consuming, we are setting ourselves up for more expensive future management by ignoring supporting services.

Second, and perhaps more important, a clear message emerging from the case studies is that ecosystem services interact and that targeting one can affect many others. The fact that models are able to explore only a small subset of ecosystem services (even within provisioning and regulating services) means that a smaller set of potential trade-offs can be quantified. Thus even if the models were able to perfectly characterize all the trade-offs among the ecosystem services that they consider, they would still underestimate the consequences of any societal choice, as many other trade-offs would remain unquantified.

Given the complexity of interactions among ecosystem services and the limited set of services directly quantified (see Chapter 9), it is a great achievement of the scenario development and modeling teams that some trade-offs were successfully visualized. But again, if model results are a simplification of reality, the simplification of the trade-offs is certain to be greater. Model results, at best, represent a crude lower bound of the expected consequences of any specific scenario. Reality will certainly be characterized by many other unforeseen changes in ecosystem services. Models offer us a means for contrasting societal choices, but history shows us that these choices can lead to far more severe consequences than models could ever predict (Ehrlich and Mooney 1983).

12.6.2 Dilemmas in Ecosystem Service Decisions: Complex Interactions of Ecosystem Services and Human Societies

Making choices about the management of ecosystem services is a prevalent feature of all human societies. In many cases, these choices have directly affected the delivery of non-target services (either positively or negatively).

Synergisms occur when ecosystem services interact with each other in a multiplicative or exponential fashion. For example, invasions of exotic plants are promoted by human disturbance (Crawley 1987). In the case of the human modification of the U.S. Laurentian Great Lakes, disturbance of the aquatic landscape facilitated the invasion of zebra mussels both by changing the composition of the local biota and physically providing a route for their spread. But not all interactions between ecosystem services need to be negative. The conservation of fishes in Bonaire not only maintained the interest of tourists, it also protected the fishery for the future and made the reef resistant to the loss of the regulatory function provided by black-spined sea urchins. Achieving successful synergistic interactions remains a major challenge in the management of ecosystem services because the strength and direction of such interactions remains virtually unknown (Sala et al. 2000).

Trade-offs may arise without premeditation: regulation of lobster fishing in the northeastern United States was motivated by a need to increase the supply of lobsters, a provisioning service, and turned out to also enhance the cultural services related to strengthening the social fabric and community organization of fishing cooperatives. Mining along the Kafue River shows how Zambians have traded off the quality of upstream wetlands while retaining the properties of drinking water and food (provisioning services) provided by the lower portions of the watershed.

As the human domination of Earth increases in extent and intensity, three important dilemmas arise:

- To what degree can human-created services substitute for ecosystem services?
- What degree of ecological complexity is needed to provide reliable ecosystem services?
- Are there limits to successfully engineering ecosystems, and what are they?

Understanding these dilemmas may help improve our decisions about trade-offs and management of complex socioecological systems.

12.6.2.1 Ecosystem Services and Human Services

Many people believe that the products of ecosystems, ranging from clear water to the beauty of a tiger, cannot be substituted for by other services. Numerous studies, however, implicitly or explicitly assume that the products of human ingenuity can provide good or at least satisfactory replacements for most ecosystem services. The degree to which ecological services can be replaced by technologically generated alternatives is very uncertain. Replaceability depends upon what services people want to replace, what technologies are available, and what other ecosystem services are (intentionally or accidentally) traded off by the technological replacement. Future technologies may allow feats that are impossible or prohibitively expensive today. On the other hand, formerly unknown or unimportant ecosystem services may be discovered to be fundamental to people or the maintenance of other ecological services.

An example of this type of dilemma is provided by water management. Humans have always altered rivers to regulate water levels. While these interventions were often successful, changes in rivers and their floodplains decreased their ability to provide regulating and supporting services, resulting in water contamination and floods. People have begun to realize that it may be less costly to enhance flood control and water quality ecosystem services via ecosystem protection rather than construct artificial water control and purification systems. In the United States, for example, New York City manages watersheds in the Catskills in ways that improve the quality of New York's drinking water. This model of ecological management improved the quality of the drinking water at a far lower cost than building a water treatment plant (Chichilnisky and Heal 1998; Heal 2000). Both forest habitat and water quality are enhanced.

This dilemma is illustrated primarily in the TechnoGarden scenario, in which societies favor the use of technology to enhance direct provision of services by ecosystems. This type of trade-off is also common in Global Orchestration, in which societies believe that, when needed, human ingenuity will find acceptable replacements for ecosystem services.

12.6.2.2 How Much Ecological Complexity Is Enough?

Humans are simplifying Earth's ecosystems, and the consequences of this simplification on the continued production of ecosystem services is uncertain. Some ecological work suggests that relatively few species performing different ecological functions can provide many ecosystem services (Tilman et al. 1996; Ewel and Bigelow 1996). However, other research indicates that while this may be true over small areas and short periods, the loss of species increases the variability of ecosystem services and increases ecosystems' vulnerability to disturbance (Peterson et al. 1998; McCann 2000).

If ecosystems could be simplified with minimal loss of ecosystem services, ecological simplification would be an ethical issue, peripheral to sustainable development. If ecosystem services are vulnerable to ecological simplification, however, maintaining and creating complex ecosystems should lie at the center of sustainable development efforts. Evidence to date suggests that complexity and redundancy are indeed fundamental to maintaining the supply of ecosystem services (Hobbs and Cramer 2003). The management dilemma that will arise is whether or not to create policies to encourage maintenance of ecological complexity. This may require discovering ways to balance short-term, local loss against long-term, regional gain. This question is, of course, related to the question of how much biodiversity (that is, landscapes, ecosystems, species, populations, and genes) is needed to effectively and sustainably produce desired ecosystem services. This dilemma is illustrated in Global Orchestration, in which ecosystems are simplified to produce immediate benefits to human well-being without regard to the future provision of ecosystem services.

12.6.2.3 To What Extent Can Ecosystems Be Engineered?

Ecological engineering offers potential for people to increase the quality and amount of ecological and human-produced services they use, while maintaining the ability of ecosystems to continue to produce ecological services (McDonough and Braungart 2002). But the goal of producing a "Garden Earth" requires that people reliably engineer ecosystems to produce desired services sustainably. Unfortunately, past ecological engineering efforts have frequently produced surprising consequences (Cohen and Tilman 1996; Holling 1986; Holling and Meffe 1996; Gunderson and Holling 2002), which suggests that we still lack the sophistication or necessary understanding to engineer ecosystems. This dilemma is illustrated in TechnoGarden, in which societies value understanding ecosystems and use that understanding to control and improve provision of ecosystem services.

There are a number of examples of land management by local people in both the old and new world that suggest that people can improve the productivity of ecosystems in a relatively sustainable way and in a fashion that does not eliminate the ability of surrounding ecosystems to provide nonagricultural ecological services. For example, research over the past decades in the Amazon found that approximately 10% of its land area is anthropogenically produced fertile soil that is more resilient to disturbance than non-anthropogenic soil (Glaser et al. 2001). Similarly, it has been suggested that pre-Columbian societies generated productive mixed aquaculture/agriculture systems in relatively unproductive parts of Bolivia (Erickson 2000). Another example of an integrated approach is the water temple system in Bali. A system of water temples was used to balance rice production, which is increased by the staggered availability of water to different fields, with the need to control rice pest populations, which increase rapidly with synchronized production across large areas (Lansing 1991). The ability of engineered ecosystems to produce a broad variety of ecosystem services rather than optimizing a single service remains largely untested, however.

12.6.3 Complex and Cascading Effects of Trade-offs

The case studies and the results from the scenarios demonstrate that trade-offs are complex and often have ramifications far beyond the decision that led to the trade-off itself. Trade-offs can affect service provision in places that are far away, they can affect other services nearby, and they can affect the future provision of ecosystem services. Whether they affect nearby services, faraway services, or future services, trade-offs are usually involve unanticipated effects on secondary services. Decisions frequently cascade through multiple ecosystem services following both known and unknown pathways. Unanticipated effects on secondary services and the multiple pathways trade-offs may take add to the complexity of ecosystem service management choices. This complexity can have serious implications for making trade-off decisions.

Lessons from the examples presented in this chapter suggest that managers can benefit by classifying their trade-off decisions, identifying the characteristics common to their decisions, and understanding the potential dilemmas that their decisions must address. Although it will be impossible to mitigate all the unknown and unanticipated effects of each decision, management schemes that focus on ''win-win'' outcomes and include sufficient redundancy within each plan will be more successful than other management schemes. Structured approaches to making decisions about ecosystem services, which take advantage of existing models and include an adaptive management approach, will have a higher likelihood of mitigating unintended consequences.

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