Chapter 2.3. **Natural Capital, Services and Human Wellbeing**

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2.3.1. Introduction

Our planet provides the essential life support system for humanity – the air we breathe, the water we drink, the food we eat, the climate in which we live, and the places, and other organisms, that we value. The global atmosphere, climate, land, ocean, and geologic systems – all components of the global Earth system, and the ecological systems on land and in the oceans that function within – are the natural capital upon which humanity depends. The flows of goods and services obtained from natural capital are dynamic and are influenced by interacting processes and feedbacks, including the effects of human activities themselves.

Some components of natural capital, often designated “natural resources”, have long been recognized and valued. Economic values have been set and markets established for such commodities as timber and other forest products, food from agriculture and fisheries, and some other natural products such as pharmaceuticals. However, nature provides many services that are not recognized by institutions and for which no markets exist, such as regulation of freshwater flow and quality, and provision of crop pollinators by ecosystems. Nonetheless, all Earth system and ecosystem services affect human well-being. The ways in which they do so are not always direct and clear, and the relationships between services from natural capital and human outcomes are thus a focus of academic debate and research. However, the importance of natural capital to the sustainable well-being of people is far from academic.

In this chapter, we discuss the variety and inter-relationships of services derived from natural capital, and examine the structure, processes, and dynamics that control the provision of these services. We consider the various forms of interactions between human use and human management of natural capital. These discussions draw on two related strands of scientific research. The first strand, related to our understanding of the planetary life support system and its dynamics, has progressed rapidly through research carried out under the auspices of four international global change programs – the International Geosphere-Biosphere Programme, the International Human Dimensions of Global Change Programme, DIVERSITAS, and the World Climate Research Program – as well as assessments done by the Intergovernmental Panel on Climate Change and the Millennium Ecosystem Assessment. This body of research has illuminated the nature of the global system and its component parts, and identified ways in which global systems provide for and respond to human activities (e.g., Steffen et al. 2005). The second strand, focused on an understanding of dynamics of ecosystems and the benefits they provide for humans, has likewise been aided by these global programs, but emerged more directly from biophysical research on the structure and function of ecosystems, including more recent research on ecosystem processes in the context of coupled human-environment systems (Pace and Groffman 1998, Chapin et al. 2002, 2009; see Chapter 1.3 for an overview of human-environment systems).

Both of these strands of research converge in the understanding of natural capital, the services that flow from it, and the factors that affect it (Fig. 2.3.1). Natural capital is more than stocks of what humankind has historically labeled natural resources (e.g., coal deposits or fish stocks); it is the capacity to produce Earth system services that are used by humans. Ecosystem services include the subset of Earth system services that are most directly involved in local human-environment interactions. Services – of the Earth system and the ecosystems embedded within it – are among the factors that affect human wellbeing. A host of human and social processes – demography, economics, politics, culture, technology and others – interact with human well-being and are also indirect drivers of human actions toward natural systems. Human actions that directly affect natural capital include drivers such as greenhouse gas emissions, land use change, nutrient mobilization, species invasion and so forth, and changes in natural capital are as also influenced by natural direct drivers such as solar activity, volcanoes, and the like.

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The chapter first addresses Earth system and ecosystem services and their relationships to natural capital. We then consider links to human outcomes. Finally we consider the dynamics of natural capital and ecosystem services as affected by key drivers, interactions among ecosystem services, and the ecological dynamics of natural capital.

2.3.2. Earth System Services and Ecosystem Services

Earth system services are those of the global system that support humans and their wellbeing. These include the climate system, the global hydrological cycle, the global atmospheric and ocean circulatory systems, the atmospheric chemical system, and other global processes that are largely abiotic although they may be influenced by biota to some extent. For example, the chemical and physical processes that maintain the stratospheric ozone shield against UV radiation are an Earth system service and are not usually included in lists of ecosystem services.

Ecosystem services are the benefits that people obtain from ecosystems. Examples are provision of food, fiber and freshwater; regulation of local air quality, runoff and floods; or educational, esthetic or spiritual benefits of wild places. Ecosystem services are intrinsically place-based, with spatial boundaries defined explicitly for the purposes of any particular ecosystem study. A long tradition of research defines an ecosystem to be a place, including all of the organisms and the components of the abiotic environment within specified spatial boundaries (Likens 1992). Many analyses, especially those of the past two decades, explicitly include humans in this definition (Lubchenco et al. 1991, M.A. 2003).

The Earth system is, in a sense, the largest ecosystem, and biological processes matter to its functioning at all scales; indeed, this is one of the major conclusions of the decades of global change research (Steffen et al 2005). For example, vegetation influences regional hydrology and climate, even though most of Earth's hydrologic cycle is controlled by ocean-atmosphere interactions that are largely abiotic. Likewise, long-term changes in the global carbon cycle reflect global tectonics, orbital dynamics, catastrophic events, and fossil fuel emissions as well as changes in photosynthesis and respiration by biota (Doney and Schimel 2007). Thus, considerations of analysis are the main reason we distinguish Earth system from ecosystem services. For example, any analysis of global atmospheric chemistry, climate or hydrology begins by considering the abiotic dynamics of the Earth system as a whole, whereas any analysis of air quality or freshwater supply begins by considering the human systems and ecosystems of the place being studied. Nonetheless, this distinction can be arbitrary, and both represent services of natural capital. In this discussion, therefore, we use Earth system services and ecosystem services more or less interchangeably.

2.3.3. Natural Capital and its Relationship to Services

The capacity of natural capital to produce services involves more than the stocks of natural resources used by humanity. It also involves the biological, chemical and physical processes that influence the state and functioning of the system. In principle, the net result of these processes can be expressed as a capacity or potential flow of earth system or ecosystem services. The realized or actual flow depends on the way the system is managed (Box 2.3.1).

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The way that natural capital is used to generate ecosystem services is crucial for understanding the rate of flow of the services, the potential future flow of the services, and for estimating values and shadow prices. As an example, we present a stylized case of a marine fishery (Clark 1976, Walters and Martell 2004). The natural capital that underpins the fishery depends on ocean hydrodynamics and biogeochemistry, habitat, and a host of biotic interactions with predators, prey, competitors and pathogens (Fig. 2.3.2). The harvesting system determines how the natural capital is used. It depends on institutions, markets, boats and equipment, business operators and fishers, technology and so forth. The harvesting system generates the instantaneous flow of caught fish usable by humans. During that process, the harvesting system causes mortality of the target species as well as non-target species (bycatch). Some kinds of fishing gear alter habitat. Thus the harvesting system alters the natural capital in ways that affect the future capacity of the natural capital to produce fish for harvest. In addition, drivers originating outside the fishery (such as climate change altering ocean hydrodynamics, or airborne pollutants altering biogeochemistry) may change the natural capital and the expected future yield of fish used by humans.

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Much, if not most, of the research on ecosystems' role in natural capital has focused on the services provided by ecosystems (Daily 1997, M.A. 2003). It is sometimes implicit that sustaining services equates to sustaining human wellbeing, a questionable assumption to which we shall return. The Millennium Ecosystem Assessment introduced a system for classifying ecosystem services that has been widely used (M.A. 2003, 2005a). Individual flows of benefits to people are classified as provisioning, regulating, cultural, or supporting services (M.A. 2003, 2005a). Provisioning services are products that people obtain from ecosystems (Table 2.3.1). Regulating services maintain the capacity or resilience of flows of other ecosystem services. These include Earth system services such as regulation of atmospheric chemistry, climate and the global hydrologic cycle. Cultural services—for example, those facets of the environment connecting to identity, such as sacred places, or valued for recreational or experiential dimensions, such as national parks—enrich the lives and social relations of people Supporting services are the ecosystem processes of primary production, nutrient cycling, species interactions (predation, competition, parasitism and so forth), population dynamics, genetics and physiology that underpin other ecosystem services. Biodiversity also contributes to supporting services. The distinction between supporting services and other kinds of services is changeable. For example, research may reveal a new regulatory role of a group of species (a new regulating service), or a new market may develop around discovery of a new natural product (a new provisioning service). While classification of services is evolving, nonetheless it is clear that supporting services and biodiversity are part of natural capital.

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In economics, goods are things that people want, and services are the performance of work for people. By this definition, ecosystems provide goods such as food, and services such as purification of freshwater. Daily et al. (1997, p. 3) comment that ecosystem services are involved in the production of ecosystem goods, and “In addition to the production of goods, ecosystem services are the actual life support functions, such as cleansing, recycling and renewal . . .”. Under this distinction, goods are mostly provisioning services, and services are mostly regulating services. In practical applications, goods and services are closely related and both depend on the natural capital and how it is used (as well as other factors). Because of this close relationship of goods and services, the Millennium Ecosystem Assessment (M.A. 2005a,b, Glossary) defined ecosystem services as synonymous with ecosystem goods and services. Following the M.A. and most of the subsequent literature, we drop the distinction between goods and services.

Research teams may choose to focus on ecosystem services or natural capital depending on the goals of a particular study. For example, a policy analysis of the tradeoffs among investments in agricultural machinery, education of workers, and regulation of soil, air and water quality might focus on the interaction of built, human and natural capital. A study of the outputs of different agricultural systems might focus on the tradeoffs among crop yield, crop diversity, soil fertility, water infiltration and water runoff by measuring these ecosystem services as a function of alternative farming practices.

Many studies of natural capital lack the data that are needed to compute monetary values and shadow prices for ecosystem services. Experience has shown that it is difficult to estimate economic values in consistent ways for diverse places (N.R.C. 2005, M.A. 2005a, Carpenter et al. 2009). Valuation is possible for some provisioning and cultural ecosystem services, but difficult or impossible for regulating ecosystem services which are critical for estimating long-term trajectories of provisioning and cultural services. Valuation is essential if economic tradeoff analyses, for example among different forms of capital, are to be conducted (Chapter 2.2).

It is useful to describe the causal chains and quantify the biophysical processes through which value is delivered, even if the final step of valuation is not possible (Carpenter et al. 2009). Descriptions of the causal chains inform decision makers of connections that they should be aware of. Each service has measurable outputs and measurable feedbacks to aspects of natural capital that affect other services. Measurements of outputs and feedbacks for different management systems provide useful comparative information about tradeoffs among multiple services, and qualitative description of curves relating various levels of management activities to service flows may help decision makers recognize thresholds that should not be transgressed.

2.3.4. Links to Human Outcomes

Sustainability and sustainable development encompasses many aspects of human well-being. Development goals include wellbeing of people (such as child survival, life expectancy, education and equality of opportunity), economic targets (wealth, production, consumption) and aspects of society (institutions, social capital, states) (Chapter 1). Many different indicators of sustainability have been used, and these differ depending on the aspects of sustainability that are most relevant for each particular study (Parris and Kates 2003). Regardless of the precise definition and measures/metrics of human wellbeing, Earth system services and ecosystem services are distinct from human outcomes (M.A. 2003).

The availability of an ecosystem service does not guarantee that it will be used effectively to increase human wellbeing. Moreover, the absence of an ecosystem service in a particular place can be overcome by the economic or technological substitute of another ecosystem service (e.g., synthetic nitrogen for cultivation), or the same service from another place (e.g., long distance transport of water via canals). As an example, consider the earth system service of global climate regulation and the local ecosystem service of food production in relation to one aspect of human wellbeing, food security. Areas of the world with similar climates can have very different crop yields because of differences in agricultural practices. Moreover, crop yield is not the same as food security. Harvest, transportation, food preservation, packaging and distribution systems, entitlements, and cultural aspects of food preparation and use, for example, all play a role in the eventual human outcome of food security. Thus similar climates can lead to different crop yields (an ecosystem service), and similar crop yields can be related to different levels of food security (an aspect of human wellbeing).

Additionally, and in a more general sense, increases in material well being of societies tend to be matched by drawdown of natural capital. While environmental management has enhanced some services (such as food and fiber production), almost all cases of economic development, over the long haul, reduce some critical services or the capacity of the ecosystem to deliver them (Kasperson, Kasperson and Turner 1995, M.A. 2005a). In some cases, coupled systems have reached tipping points, some of which involved natural capital or services, with dramatic societal consequences (e.g., Tainter 1988 ; Diamond 2005; Redman 1999, Gordon et al. 2008). Indeed, some researchers note that society now has the capacity to trigger Earth system tipping points (Schellnhuber 2009).

Earth system services and ecosystem services are important factors in human wellbeing, but they are not the only factors. Therefore human wellbeing cannot be predicted from services alone.

Governance, institutions, technology, and social capital, for example, have important effects on human wellbeing. Multiple interacting causes, and the complex nature of wellbeing itself, make the study of wellbeing a daunting challenge. Nonetheless, ecosystem services affect human wellbeing in fundamental and quantifiable ways, such as provision of food, fuel and fiber, regulation of water flows and water quality, and flood protection (M.A. 2005a). Natural capital is often linked more directly to wellbeing of the most vulnerable members of society than it is to the wellbeing of relatively wealthy people who are connected to nature by long complicated supply chains. Nonetheless, many ambiguities and uncertainties exist in the linkage of ecosystem services to human wellbeing (M.A. 2005b). Further research is needed to understand how the full spectrum of ecosystem services affect all aspects of human wellbeing, how regulating ecosystem services affect risk and trajectories of human wellbeing over time, how ecosystem services interact with other non-environmental determinants of human wellbeing, and how flows of ecosystem services across the wealth spectrum affect the most vulnerable members of society (Carpenter et al. 2009).

In practice, any development program or research project must focus on particular aspects of human wellbeing and evaluate changes in them using indicators. Parris and Kates (2003) found that sustainability indicators have many motives, such as management, advocacy, participatory consensus building, and research. Not surprisingly, they found that the various indicators differ in their emphasis of different development goals. Moreover, computation of any particular indicator requires assigning weights to the various statistics that go into the indicator (Carpenter et al. 2009). Assigning weights is a value-laden process and therefore subject to debate. Parris and Kates (2003, p. 559) conclude that ". . . there are no indicator sets that are universally accepted, backed by compelling theory, rigorous data collection and analysis, and influential in policy". To some extent this lack of consensus is due to the diversity of goals in characterizing sustainable development. However, some of the difficulty is due to confusion of terminology, data and methods of measurement. These latter problems can and should be resolved by joint effort of the research, assessment and management communities.

2.3.5. Drivers of Change in Natural Capital and Ecosystem Services

Humans change the earth system, including the ecosystems within it, in many ways (Chapter 1.2). In this section we briefly discuss the immediate or direct factors, often called drivers, of change in natural capital (Fig. 2.3.1). Several studies have evaluated drivers of change in ecosystems or their services (Vitousek 1994, Vitousek et al. 1997b, M.A. 2005b, Steffen et al. 2004, Turner et al. 2007, Heinz Center 2008). Here we focus on climate change, land use and conversion, mobilization of plant nutrients, and invasive species, which are included on most lists of critical drivers of change in ecosystems, the Earth system, or natural capital.

2.3.5.1. Climate Change

Climate-related variables that affect ecosystems include temperature and precipitation (especially extremes, but also central tendencies), sea level in the case of coastal systems, ice cover, and pH for marine systems in general. Global average temperature increased about 0.6° C from the mid-1800s to 2000, with a great deal of temporal and spatial variability. Precipitation increased about 0.5% to 1% per decade in the 20th century over mid- and high latitudes of the Northern

Hemisphere continents, and decreased about -0.3% per decade over most of the sub-tropical land areas. Global average sea level rose 10-20 cm during the 20th century.

A number of recent syntheses illustrate the complex and cascading effects of climate change on other components of the Earth system, including ecosystems (Field et al. 2007, IPCC 2007, USGCRP 2009, NRC 2010). Climate changes alter habitats and species assemblages, influence biogeochemical processes, and change the vulnerability of species and ecosystems to fire, disease, and other disturbances; many of these changes feedback to influence the climate system.

In addition to their effects on climate, rising levels of CO_2 in the atmosphere have other effects on ecosystems. CO_2 concentration affects plant growth, competition among plant species and plant biodiversity, and interacts in complex ways with effects of nitrogen and temperature (Reich et al. 2009, Shaw et al. 2002). Rising atmospheric CO_2 also increases the concentration of carbonic acid in the ocean. Ocean pH has declined about 0.002 units / year since the late 1980s based on North Pacific Ocean data (Dore et al. 2009). Further declines in pH are expected as atmospheric CO_2 concentrations increase (NRC 2010).

Projected climate changes and effects on ecosystems and their services are an active and rapidly developing area of research. The Millennium Ecosystem Assessment scenarios show that climate effects on ecosystem services are likely to become more important over 2000-2050, joining land use change, nutrient mobilization and invasive species as the dominant drivers of change in ecosystems and their services.

2.3.5.2. Land Conversion

Humans convert land to other uses in order to derive livelihoods or other benefits, such as recreation, and in so doing alter the mix of ecosystem services provided by the land (Foley et al. 2005, Ellis and Ramankutty 2008). In some cases land conversion is unintentional, for example when soil is salinized by irrigation projects that have inadequate drainage. Agriculture is the largest human use of land, the largest human use of freshwater, and the largest human source of greenhouse gas emissions to the atmosphere (IPCC 2007, Smith et al. 2008). The dominant forms of rapid land conversion from 1980-2000 were deforestation, dryland degradation, agricultural expansion and abandonment, and urban expansion which, among other things, increases the impervious surface area of the earth (Lepers et al. 2005). While endogenously connected (e.g., agricultural expansion leads to deforestation and dryland degradation), these drivers are likely to remain the dominant into the future with large impacts on provisioning and regulating services (Lambin et al. 2003).

Model projections of land-use indicate that this will continue to be a powerful driver of change in natural capital and ecosystem services over the next few decades (M.A. 2005b). Perhaps 10% to 20% of current grassland and forestland will be converted for agriculture and prime agricultural lands will continue to be lost to urban expansion by 2050 (M.A. 2005b). Nonetheless, there are considerable differences among scenarios because land change is so sensitive to changing political economic conditions. Thus these projections are likely to change as the science evolves (Turner et al. 2007).

2.3.5.3. Nutrient Mobilization

The plant macronutrients nitrogen and phosphorus are widely used in agriculture to increase crop yields. In addition, nitrogen compounds are released to the environment through fossil fuel combustion and other human-mediated activities (Vitousek et al 1997, Galloway et al. 2008). Reactive nitrogen is fixed from the air by an energy-intensive industrial process. The annual rate of human release of reactive nitrogen compounds to the environment increased by a factor of 12.5 (15 Tg y^{-1} to 187 Tg y^{-1}) from 1860 to 2005 (Galloway et al. 2008). Excess reactive nitrogen in the environment pollutes groundwater, surface water and air, and decreases biodiversity by favoring growth of weedy plants.

Phosphorus is also widely used in fertilizers. It is obtained from mined phosphate rock. Fertilizer phosphorus production rose steadily from about 1945 to the 1990s, when it appeared to level off (Bennett et al. 2001, M.A. 2005b). Livestock excreta play an increasingly important role in the global phosphorus cycle. Phosphorus is needed to increase crop yields in some parts of the world, such as many parts of Africa and Latin America. In tropical forest lands, deforestation can remove significant amounts of phosphorus (REF). On the other hand, excess phosphorus is responsible for harmful algal blooms in freshwater supplies in regions where fertilizer applications or livestock densities are high (Carpenter et al. 1998).

Future changes in mobilization of nitrogen and phosphorus depend on food demand, including the proportion of meat in human diets, agricultural production, and intensity of fertilizer use in agriculture. In addition, nitrogen mobilization depends on fossil fuel use. Scenario analyses indicate that nitrogen oxide release to the environment will rise from about 30.5 Tg y^{-1} in 2000 to 39 to 46 y^{-1} in 2050 (M.A. 2005b). The need for phosphorus will also be great. However, some of the demand for phosphorus could be met by more efficient use of phosphorus in manure and waste. Improved efficiency in phosphorus use will become more critical if we encounter global shortages of the nutrient as anticipated by some analysts (Gilbert 2009).

2.3.5.4. Species Invasion

Invasive species are animals, plants or microbes that spread in space, either occupying new habitats or increasing in abundance in areas already occupied. Biological invasions are a global phenomenon affecting most of the world’s ecosystems (Mack et al. 2000). Not all invasions are harmful; after all, it is important to note that a high percentage of the world’s food supply comes from introduced species (M.A. 2009b). Nonetheless, some species invasions are harmful. Species invasions are important drivers of extinction rates as well as local extirpations that reduce biodiversity (Mooney and Hobbs 2000). For example, 42% of species on the U.S. Threatened or Endangered Species List are at risk primarily because of alien invasive species (Pimentel et al. 2005). Invasions also have adverse effects on productivity of croplands, livestock, forestry and fisheries (Mack et al. 2000). In some parts of the tropical world invasive ferns lead to land abandonment and the cutting of more forest to take the place of the invaded lands (Mooney and Hobbs 2000; Schneider 2004). Such invasive cases are not limited to the tropics. In the United States, environmental damages due to invasive species were valued at $120 billion per annum (Pimentel et al. 2005).

Long-term future trends in species invasions are difficult to forecast. Important factors in species invasions include globalization of trade, human mobility, climate change and land use change. Ongoing increases in these factors are likely to increase species invasions (M.A. 2009b).

2.3.5.5. Interactions Among Drivers

Changes in natural capital or the services it provides rarely have single causes. Instead they are driven by interactions among multiple drivers. For example, climate change and globalized markets, interacting with local economic opportunities and institutional factors, may affect an agricultural region through shifts in patterns of land conversion, the mix of crops planted, or tillage practices. These changes, in turn, can affect the balance of runoff versus infiltration in the water cycle, fertilizer use and water quality, and the risk of species invasions. The resulting changes in ecosystem services can feed back to affect the drivers and the human factors affecting them. They could, for example, evoke institutional changes in response to perceived or anticipated resource degradation, or shift income distributions as environmental change alters patterns of winners and losers. In cases of deforestation and desertification, several drivers may amplify each others' effects, a synergy that increases the magnitude of ecosystem change (Geist and Lambin 2002, 2004). For example, the search of productive agricultural activities in parts of the tropics, driven by combined subsistence and commercial pressures in rapidly changing socioeconomic conditions leads to low input agricultural activities in the face deforestation which, in turn, reduces phosphorus capture by forest canopy, regional evapotranspiration with likely precipitation impacts, and the loss of slow maturing species, often the most valuable timber (Lawrence et al. 2007; Turner 2009). . The set of potential interactions among drivers is vast, and ongoing research is likely to reveal great complexity of factor interactions that drive change in natural capital.

2.3.6. Interactions of Ecosystem Services

The elements of natural capital do not act in isolation. They interact, and the interactions are potentially complex and unpredictable. Moreover, the outcome of the interactions depends on way that the natural capital is used. Different ways of using natural capital yield different mixtures of ecosystem services. A hypothetical example of two scenarios for managing an agricultural ecosystem is presented in Fig. 2.3.3. Scenario A results in a rather balanced output of six ecosystem services, although meat production is low. Scenario B emphasizes high meat production but achieves relatively low flows of the other five ecosystem services.

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To manage the mixture of services that can be obtained from any ecosystem or the Earth system itself, it is necessary to know which services are provided by the system, and how management practices affect the flows of the various services that can be generated from the natural capital of the system, in the present and in the future (Daily and Matson 2008). Knowledge of these flows, their interactions, and their responses to alternative management practices can be used to balance the mix of ecosystem services flowing from a region. A typology of ecosystem service interactions has been used to identify ecological leverage points where relatively small management investments can yield relatively large benefits for ecosystem service flows (Bennett et al. 2009). For example, model scenarios for the Willamette Basin of Oregon, USA showed that high scores for a variety of ecosystem services were associated with high scores for biodiversity (Nelson et al. 2009). In contrast, scenarios involving more development had higher commodity production values, but lower levels of biodiversity conservation and ecosystem services. However, payment for carbon credits helped mitigate this tradeoff.

Regulating services are particularly important for determining the future potential flows of ecosystem services that can be obtained from a specified region. The future flows are particularly important for determining the inclusive wealth represented by the natural capital (Chapter 2.2). Unfortunately, regulating ecosystem services are often not apparent to decision makers and institutions for managing them are absent. In some cases, the technical capacity to measure or even identify regulating services is lacking. As a result, management systems often neglect regulating ecosystem services while increasing flows of provisioning services which are more apparent and easily measured (M.A. 2009b, Chapter 12). Thus natural capital is reduced and future flows of ecosystem services are diminished. In agricultural ecosystems, for example, neglect of regulatory services has increased the risk of unexpectedly large changes in water quality, floods and landslides, fires and drought duration (Gordon et al. 2008).

While regulating services are particularly important to interactions across time, it is important to recognize that natural capital and its services are also connected across space (Fig. 2.3.4). Thus, analysis of natural capital and services require a place-based approach where spatial scales are specified as part of the analysis. To assess the effects of scale, a nested hierarchy of scales may be used, as in the case of the Southern Africa Millennium Assessment (Biggs et al. 2004). Rosenzweig (2003) shows that some aspects of biodiversity – a key component of natural capital – can persist at certain spatial scales even in landscapes that are used intensively for production of ecosystem services.

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2.3.7. Dynamics of Natural Capital

The dynamics of ecosystems underpin the dynamics of natural capital. A family of models that has been applied to ecosystems as well as social systems derives from the theory of complex adaptive systems. The biosphere and human-environment systems are special cases of complex adaptive systems (Levin 1998, 2006; Norberg and Cumming 2008). Key features of complex adaptive systems (Levin 1998) are (1) variety of interacting units (e.g. individual organisms or people), including mechanisms to generate variety (such as sexual reproduction, social innovation, or technological innovation), (2) localized interactions (i.e. interactions among individual units are patchy or heterogeneous in space and time), (3) selection (i.e. individual units are differentially successful at meeting some criterion, so that over a given interval of time some units persist while others fail), and (4) emergence of structures with characteristic spatial extents that last for a certain period of time (for example patches of a particular kind of forest on a natural landscape, or cities). These are minimal conditions for complex adaptive systems; further complexity can be generated for example by interactions across spatial scales, or nonlinear dynamical relationships (M.A. 2005b Chapter 3, Norberg and Cumming 2008).

Accordingly, we should expect that components of natural capital are distributed in patches in space and time. Cod are most abundant in marine areas with the right combination of bottom topography and currents; caribou or wildebeest migrate seasonally along certain routes; wild rice is found in quiet water near the edges of lakes and rivers; and so forth. Human action, especially land and resource management, is an important factor in the patch structure of natural capital and ecosystem services on landscapes and seascapes, and over time.

Natural capital of a given landscape or seascape may have different patch structures, different seasonality, or different trends over time. Such differences are often encapsulated as “different space and time scales”. While this short phrase is sometimes useful, it belies enormous complexity in spatial and temporal data. Understanding the dynamics of natural capital is a topic of great intellectual richness, occupying many researchers from many subdisciplines of earth system science. Here we will focus on just a few points that are essential for the purposes of this book.

2.3.7.1. Elements of Natural Capital are Highly Interconnected

Components of natural capital of the planet, or any locale, are numerous and highly connected, such that changes in part of the system readily cascade to affect other parts. These interactions require significant expansion beyond the traditional models of resource economics. The traditional models made great contributions to our understanding of production and exploitation rates of single resources, such as fisheries or forest production. To analyze ecosystem services and natural capital, more dimensions must be added to account for the various interacting ecosystem services, spatial interactions must be accounted for, nonlinear complex processes must be analyzed, and the interactions with other sectors of the economy and institutions must be considered.

2.3.7.2. Elements of Natural Capital Interact Across Locales and Spatial Scales

Elements of natural capital and the services that flow from it interact among landscape patches in any given region. For example, land use around headwater streams affects the balance of aquifer recharge or runoff, nutrient retention or export, and thereby affects freshwater flows and water quality downstream. The presence or absence of migration corridors affects movement of native and invasive species, and thereby affects wildlife and forest production in separate patches of forest. The condition of coastal mangroves, an important nursery habitat for fishes, affects the yield of nearby fisheries.

Important interactions occur across different spatial extents. Global processes such as climate affect regional ecosystem services. In the reverse direction, land use and land cover affect carbon storage, greenhouse gas flux, evapotranspiration and albedo, thereby affecting climate at larger scales. Agricultural practices affect fluxes of nutrients to surface waters and ammonia to the atmosphere, and thereby influence large-scale eutrophication of downwind land- and seascapes.

Importantly, a system that appears sustainable at a particular spatial scale may contain smaller components that are not sustainable, or be embedded in a larger system that is not sustainable.

For example, wildebeest are dominant herbivores for much of eastern Africa, and the functioning of various parks and nature reserves, for example the Serengeti and Mara of northern Tanzania and southern Kenya, respectively, require large herds of the species to be present for parts of the year. Indeed, theses parks and reserves have been set aside specifically to conserve and preserve Africa's biotic diversity and have become major sources of income from ecotourism. The presence of wildebeest in the Serengeti-Mara ecosystem, however, is potentially threatened by land agricultural land expansion into the breeding and calving grounds of the wildebeest which reside outside the preserves. This expansion has led to substantial reductions of wildebeests in parts of the reserves in the recent past (Homewood et al. 2001), demonstrating that sustainability of the Serengeti-Mara reserve system is profoundly affected by character and scale of land uses beyond their bounds.

2.3.7.3. Elements of Natural Capital Interact Across Time

2.3.7.3.1. History Matters

Present-day services depend on the history of the natural capital used to generate them. Studies of Earth system history reveal no balance of nature. Moreover, the ongoing changes in the Earth system and ecosystems have been influenced by human action for thousands of years (Dearing 2007a,b). Thus the ecosystems that we see today are the product of human and natural events that may have originated far in the past, and current-day changes in ecosystem structure or processes may affect ecosystem services for a long time into the future (Carpenter 2002). Often these changes are driven by human actions that alter persistent, slowly-changing features of the ecosystem. Examples of slowly-changing features are geomorphology of landscapes and seascapes, soils and sediments, long-lived organisms such as trees or whales, and ecological legacies such as dead tree trunks (which may provide habitat for other organisms for decades). At a global scale, the long residence time of CO_2 in the atmosphere causes long delays in the response of climate to changes in the carbon cycle.

Ecosystems are subject to extensive changes that are difficult to reverse (Walker and Meyers 2004). Rangeland degradation is among the well-studied examples. In rangelands, grassy cover is maintained by the interaction of grazing and fire. When rangelands are overgrazed, woody inedible shrubs become more common. When grass cover becomes too sparse to carry a fire, woody vegetation takes over and pastoral ecosystem services are lost for a long time. There are many other examples of massive change that is difficult or impossible to reverse, with long-lasting consequences for ecosystem services (Carpenter 2003, M.A. 2005b Chapter 3, Scheffer 2009).

2.3.7.3.2. Natural Capital Depends on Disturbance Regime

Disturbance regime is the frequency and magnitude of mortality events characteristic of a given ecosystem, such as the fire regime of a forest or grassland, or the flood regime of a river valley. Disturbance regime is the result of interaction between exogenous events and the condition of the ecosystem; for example a lightning strike will start an extensive fire in a forest with a high density of fuel, but the fire will not spread if the fuel density is low. The adaptations of individual organisms, species composition, biogeochemical processes, and spatial organization of ecosystems depend on the disturbance regime.

Changing the disturbance regime can have strong effects on ecosystem processes and therefore on natural capital and the services that derive from it. Examples are known from many types of ecosystems. Interactions of fire history and fuel patterns, insect outbreaks and climate change can alter future fire regimes, production and nutrient cycling of forests (Turner 2010). Levee construction breaks connections between rivers and their floodplains, thereby changing the delivery of nitrogen, phosphorus and sediments to estuaries (Naiman et al. 2005). Coastal engineering has optimized nearshore habitats for average ocean conditions while decreasing the capacity of coastal ecosystems to recover from catastrophic storms (Pilkey and Pilkey-Jarvis 2007). In some cases, however, the long history of human and natural disturbance in concert with one another may become the basis on which the ecosystem and its services depend. Examples include natural and anthropogenic burning of grasslands in parts of Africa that support large wild game and livestock herds, and forests in parts of Yucatan that appear to regenerate rapidly from human disturbance.

In managing natural capital, it is important to consider the role of disturbance regime, especially large rare events. Managing for average conditions is not likely to succeed for long, and may create new vulnerabilities to catastrophe.

2.3.8. Conclusions

To be added.

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Box 2.3.1. **Manufactured and Natural Capital.**

Built or manufactured capital is a useful point of comparison for understanding the concept of natural capital and its relationship to services.

The built capital of a steel mill is its capacity to produce steel from raw materials such as iron ore, coal and so forth. This capacity depends on the state of the machinery, the way that the mill is used and managed, the skill and organization of the mill workers, the location of the mill, the time period that the mill is in operation, and other factors. Thus the value of the mill depends on its use and the context of that use. Importantly, as shown in Chapter2.2, the value of the mill depends on its projected use over time. From this information, one can write an equation for the future values of the mill and compute a shadow price.

The natural capital of a farm is the farm's capacity to produce food of various kinds (including cultivated plants, wild plants, domestic and wild animals), runoff of surface water of a specified quality, infiltration of groundwater of a specified quality, store carbon and mineral nutrients, support various wild plant and animal species (such as pollinators, birds that eat pest insects, and plants and animals that people enjoy), absorb and reflect solar radiation (albedo, which affects local climate), and contribute to the esthetics of a rural landscape. Thus in our example the farm has more outputs than the relatively simple case of the steel mill. As in the case of the steel mill, the capacity of the farm to produce these services depends on the state of the farm, how it is used and managed, the skill and organization of the farm workers, the farm's location, time period over which it is used and other factors. The concept of natural capital for the farm also depends on how it is aggregated (e.g. as a whole farm, versus field-by-field, or by functional components such as soils, plants, animals and so forth). Here we are considering the entire farm as a whole.

In principle one could write equations for the potential flows of each service from the farm: the various foods, surface water volume and quality, infiltrated water volume and quality, carbon storage, mineral nutrient storage, various wild plants and animals that are not consumed by people but contribute to the natural capital, albedo, and esthetics. These equations would include positive interactions (for example crop production practices that maintain yields and also increase carbon storage and infiltration of high-quality groundwater) and negative interactions (for example animal rearing practices that increase meat production while degrading quality of infiltrated and runoff water, and add nitrogen trace gases to the air). From these equations and appropriate data, one can compute shadow prices.

At a larger spatial scale, one can consider capitals, values and shadow prices of a region that includes both farms and steel mills. The interactions of built, natural, social and human capital needed to address such questions are addressed in Chapter 2.2.

Table 2.3.1. Classification and definitions of ecosystem services used by the Millennium Ecosystem Assessment (MA 2005).

Category	Service	Examples
Provisioning services: products that people obtain from ecosystems	Food	Crops, livestock, aquaculture, fisheries, wild plant and animal foods
	Fiber	Timber, wood fuel, cotton, hemp, silk
	Genetic resources	Crop cultivars
	Biochemicals	Pharmaceuticals, natural products
	Fresh water	Ground water, surface water
Regulating services: processes that maintain the capacity or resilience of flows of provisioning services (e.g. water regulation) and benefits that people obtain from regulation of the biosphere (e.g. climate regulation)	Air quality regulation	Net removal of ozone, ammonia, NO_x, SO_2, particulates and CH_4 from air
	Climate regulation	CO2 sink; regional effects of vegetation on albedo, air temperature, precipitation
	Water regulation	Ecosystem effects on timing and magnitude of runoff, flooding and aquifer recharge
	Erosion regulation	Effect of land use and land cover on erosion of soil
	Water purification	Removal or sequestration of chemical pollutants (such as nitrate, phosphate, or organic compounds) and sediment by wetlands, lakes and rivers
	Disease regulation	Effects of ecosystems on disease vectors (e.g. mosquitoes or ticks), disease reservoirs (e.g. snails or mice) and pathogens that cause diseases such as malaria, schistosomiasis or Lyme disease.
	Pest regulation	Control of crop pests by natural enemies, such as bird predation on insects that attack crops
	Pollination	Pollination of crops by bats, bees, birds etc.
	Natural hazard regulation	Mitigation of floods by coastal wetlands; mitigation of tsunamis by mangroves and coral reefs
Cultural services: Nonmaterial benefits that people receive from ecosystems that enrich their lives and	Spiritual and religious values	Sacred groves and other sites protected for their spiritual significance

social relations		
	Knowledge systems	Traditional information useful for managing ecosystem services
	Educational values	Use of ecosystems for teaching about natural processes
	Inspiration	
	Aesthetic values	Values attached to pleasing natural landscapes
	Social relations	
	Sense of place	
	Cultural heritage	
	Recreation and ecotourism	

Figure 2.3.1. Major earth system interactions of natural capital.

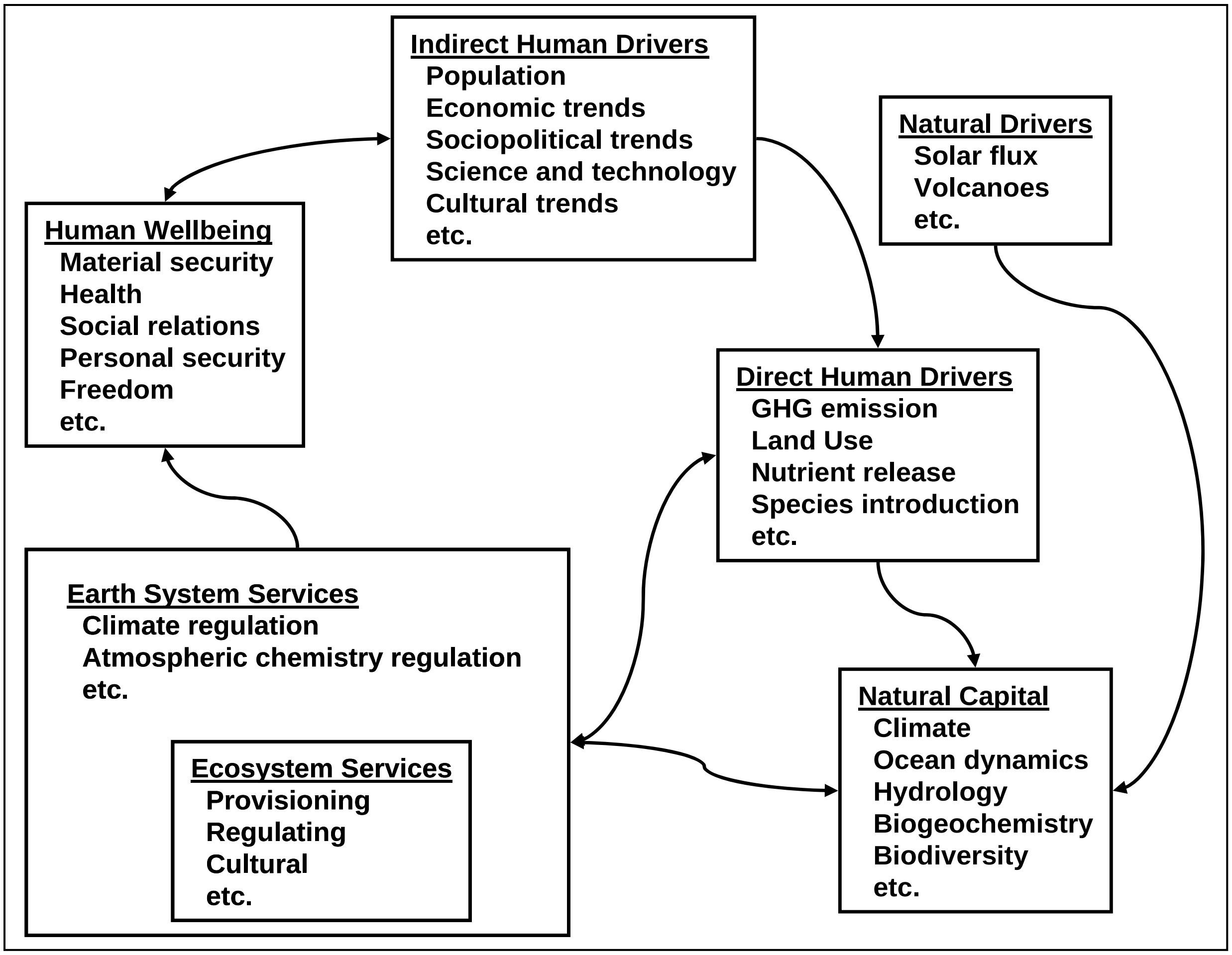

Figure 2.3.2. Linkage of natural capital and ecosystem services for a marine fishery.

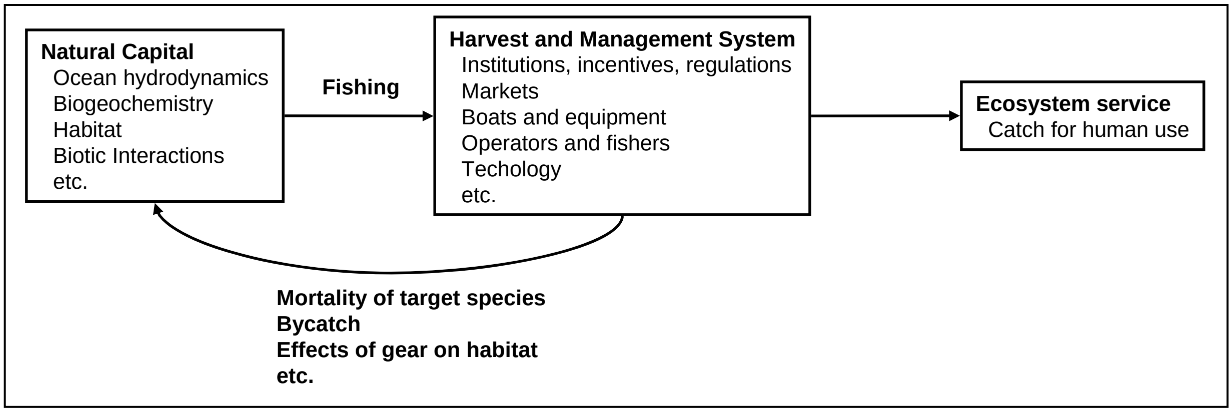

Figure 2.3.3. Example of different sets of ecosystem services from the same agricultural ecosystem derived from different management practices. Each ecosystem service is represented by a vertex of a polygon as shown in the Key. In Scenario A (gray polygon) the management practices yield relatively high grain production, relatively low meat production, and relatively high carbon storage in the soil, water quality, recharge of groundwater, and flood control. In Scenario B (white polygon) the management practices yield relatively low grain production, relatively high meat production, and relatively low carbon storage in the soil, water quality, recharge of groundwater, and flood control.

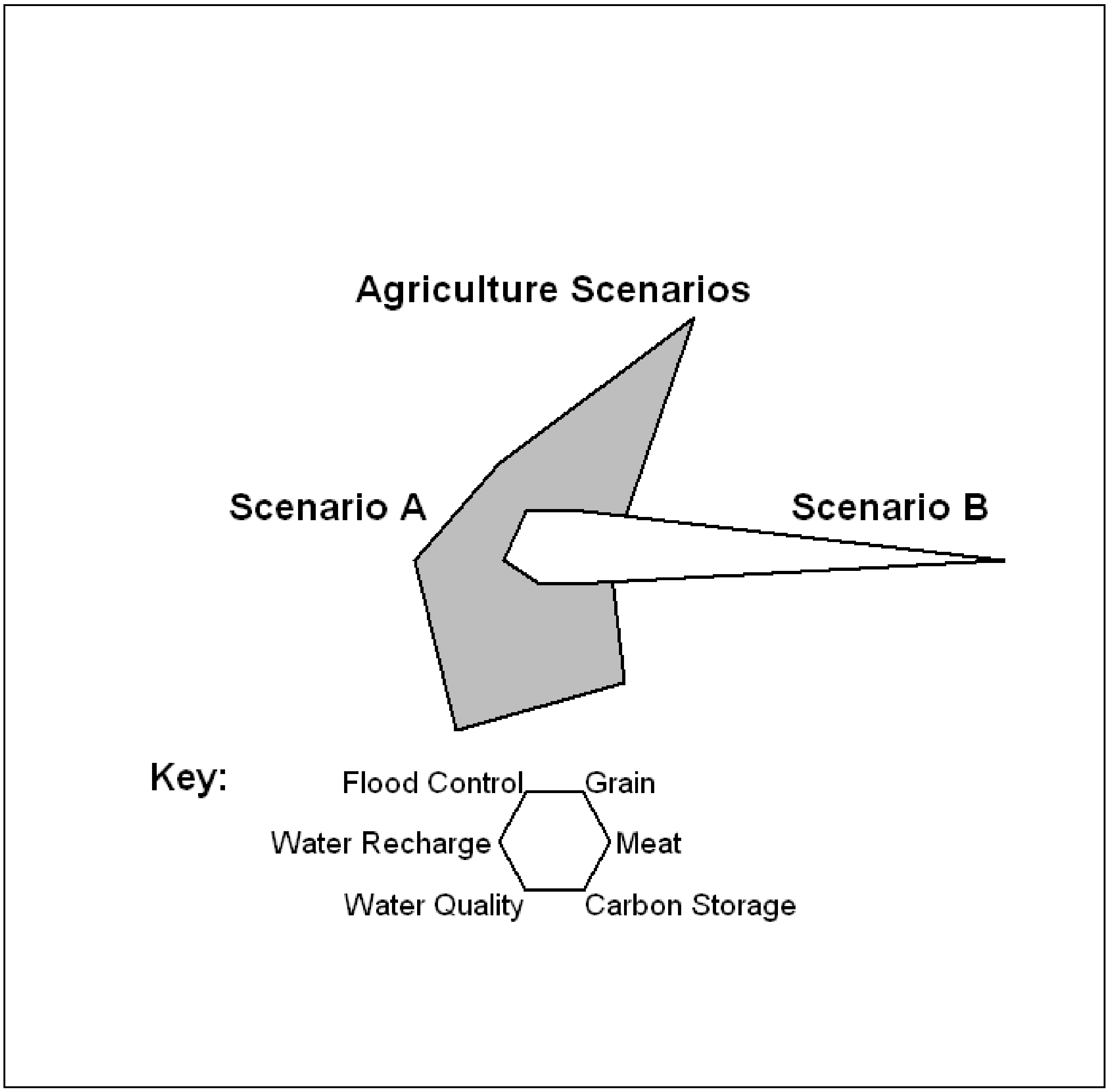

Figure 2.3.4. Interactions of drivers, natural capital, service flows, and human wellbeing across spatial scales are common.