Chapter 7

# Drivers of Change in Ecosystem Condition and Services

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## BOXES



## FIGURES



## TABLES



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*This appears in Appendix A at the end of this volume.

## Main Messages

**A driver is any natural or human-induced factor that directly or indirectly causes a change in an ecosystem.** A *direct driver* unequivocally influences ecosystem processes. An *indirect driver* operates more diffusely, by altering one or more direct drivers. Millennium Ecosystem Assessment categories of indirect drivers of change are demographic, economic, sociopolitical, scientific and technological, and cultural and religious. Important direct drivers include changes in climate, plant nutrient use, land conversion, and diseases and invasive species.

**World population, a key indirect driver, will likely peak before the end of the twenty-first century at less than 10 billion people.** The global population growth rate peaked at 2.1% per year in the late 1960s and fell to 1.35% per year by 2000, when global population reached 6 billion. Population growth over the next several decades is expected to be concentrated in the poorest urban communities in sub-Saharan Africa, South Asia, and the Middle East. Populations in all parts of the world are expected to experience substantial aging during the next century. While industrial countries will have the oldest populations, the rate of aging could be extremely fast in some developing countries.

**Between 1950 and 2000, world GDP grew by 3.85% per year on average, resulting in an average per capita income growth rate of 2.09%.** In the MA scenarios, per capita income grows two to four times between 2000 and 2050, depending on scenario. Total economic output grows three to six times during that period. With rising per capita income, the structure of consumption changes, with wide-ranging potential for effects on ecosystem condition and services. At low incomes, demand for food quantity initially increases and then stabilizes. Food expenditures become more diverse, and consumption of industrial goods and services rises. These consumption changes drive area expansion for agriculture and energy and materials use. In the MA scenarios, land used for agriculture and biofuels expands from 4.9 million square kilometers in 2000 to 5.3–5.9 million square kilometers in 2050. Water withdrawals expand by 20–80% during the same period.

In the 200 years for which reliable data exist, the overall growth of consumption has outpaced increases in materials and energy efficiency, leading to absolute increases of materials and energy use.

**Nations with lower trade barriers, more open economies, and transparent government processes tend to have higher per capita income growth rates.** International trade is an important source of economic gains, as it enables comparative advantage to be exploited and accelerates the diffusion of more efficient technologies and practices. Where inadequate property rights exist, trade can accelerate exploitation of ecosystem services.

**Economic policy distortions such as taxes and subsidies can have serious environmental consequences, both in the country where they are implemented and abroad.** Subsidies to conventional energy are estimated to have been $250–300 billion a year in the mid-1990s. Changes in greenhouse gas emissions in the MA scenarios range from negative (a decline of 25%) to positive (160%), depending on overall economic growth and subsidy reductions. The 2001–03 average subsidies paid to the agricultural sectors of OECD countries were over $324 billion annually. OECD protectionism and subsidies cost developing countries over $20 billion annually in lost agricultural income.

Since the mid-twentieth century, public sector investments in crop research and infrastructure development have resulted in substantial yield increases worldwide in some major food crops. These yield increases have reduced the demand for crop area expansion arising from population and income growth.

**Among the main direct drivers, Earth's climate system has changed since the pre-industrial era, in part due to human activities, and is projected to continue to change throughout the twenty-first century.** During the last 100 years, the global mean surface temperature has increased by about 0.6° Celsius, precipitation patterns have changed spatially and temporally, and global average sea level rose 0.1–0.2 meters. The global mean surface temperature is projected to increase 1.4–5.8° Celsius between 1990 and 2100, accompanied by more heat waves. Precipitation patterns are projected to change, with most arid and semiarid areas becoming drier and with an increase in heavy precipitation events, leading to an increased incidence in floods and drought. Global mean sea level is projected to increase by 0.05–0.32 meters in the 1990–2050 period under the MA scenarios (0.09–0.88 meters between 1990 and 2100).

**Plant nutrient application is essential to food production, but current methods of use contribute to environmental and socioeconomic problems caused by greenhouse gas emissions, eutrophication, and off-farm hypoxia.** Nitrogen application has increased eightfold since 1960, but 50% of the nitrogen fertilizer applied is often lost to the environment. Improvements in nitrogen use efficiency require more investment in technologies that achieve greater congruence between crop nitrogen demand and nitrogen supply from all sources and that do not reduce farmer income. Phosphorus application has increased threefold since 1960, with steady increase until 1990, followed by leveling off at a level approximately equal to 1980s applications. These changes are mirrored by phosphorus accumulation in soils, which can serve as an indicator of eutrophication potential for freshwater lakes and P-sensitive estuaries.

**Land cover change is a major driver of ecosystem condition and services.** Deforestation and forest degradation affect 8.5% of the world's remaining forests, nearly half of which are in South America. Deforestation and forest degradation have been more extensive in the tropics over the past few decades than in the rest of the world, although data on boreal forests are especially limited, and the extent of change in this region is less well known. Approximately 10% of the drylands and hyper-arid zones of the world are considered degraded, with the majority of these areas in Asia. Cropped areas currently cover approximately 30% of Earth's surface. In the MA scenarios, cropped areas (including pastures) increase 9–21% between 1995 and 2050.

**Human-driven movement of organisms, deliberate and accidental, is causing a massive alteration of species ranges and contributing to changes in ecosystem function.** In some ecosystems, invasions by alien organisms and diseases result in the extinction of native species or a huge loss in ecosystem services. However, introductions of alien species can also be beneficial in terms of human population; most food is produced from introduced plants and animals.

## 7.1 Introduction

This chapter examines indirect and direct drivers of change in ecosystem services (the two right boxes in the MA conceptual framework; see Chapter 1 for the diagram and description of the conceptual framework). The goal is to provide an overview at the global level of important drivers of ecosystem condition and the ability to deliver services that improve human well-being.

It is important to recognize that this chapter does not cover the remaining two boxes of the framework—the mechanisms by which the drivers interact with specific ecosystems to alter their condition and ability to deliver services and the effects on human well-being. That discussion is left to the individual condition and services chapters in the *Current State and Trends* volume and to later chapters in this volume. For selected driver categories, we do provide a brief overview of some general ecosystem consequences and some review of the range of values in the scenarios. The MA conceptual framework is not the only way to organize an assessment of ecosystems. Other popular frameworks that examine human-environment interactions include the ecological footprint (Wackernagel and Rees 1996), IPAT and its derivatives (Ehrlich and Holden 1971; York et al. 2003b), and consumption analysis (Arrow et al. 2004).

The MA definition of a driver is any natural or human-induced factor that directly or indirectly causes a change in an ecosystem. A *direct driver* unequivocally influences ecosystem processes. An *indirect driver* operates more diffusely, by altering one or more direct drivers. The categories of global driving forces used in the MA are: *demographic, economic, sociopolitical, cultural and religious, science and technology,* and *physical and biological*. Drivers in all categories other than physical and biological are considered indirect. Important direct (physical and biological) drivers include changes in climate, plant nutrient use, land conversion, and diseases and invasive species.

This chapter does not include natural drivers such as solar radiation, natural climate variability and extreme weather events, or volcanic eruptions and earthquakes. Although some of these can have significant effects on ecosystem services (such as the explosion of the Krakatoa volcano in 1883, which resulted in lower temperatures globally for several years, with negative impacts on agriculture worldwide), space limitations preclude their inclusion. The focus here is on anthropogenic drivers.

## 7.2 Indirect Drivers

We begin this chapter with a discussion of indirect driver categories—demographic, economic, sociopolitical, cultural and religious, and science and technology.

### 7.2.1 Demographic Drivers

The number of people currently residing on Earth is widely acknowledged to be an important variable in influencing ecosystem condition. There is also a growing recognition that how population is distributed across age groups, urban and rural regions, living arrangements, and geographic regions affects consumption patterns and therefore ecosystem impacts. These influences are also moderated by resources available to individuals, how they choose to allocate them (economic, sociopolitical, and cultural drivers), and the changing technical relationships needed to convert raw materials provided by ecosystems into services of value to humans (science and technology drivers). In this section, we address population dynamics, focusing on current conditions, projections of the future, and the primary determinants of population change: fertility, mortality, and migration.

#### *7.2.1.1 Current Conditions*

Global population increased by 2 billion during the last quarter of the twentieth century, reaching 6 billion in 2000. During that time, birth rates in many parts of the world fell far more quickly than anticipated, and life expectancies—with some notable exceptions—improved steadily. Now population growth rates are declining nearly everywhere. The global growth rate peaked at 2.1% per year in the late 1960s and has since fallen to 1.35% (see Table 7.1), and the annual absolute increment of global population peaked at about 87 million per year in the late 1980s and is now about 78 million (United Nations 2003a). This does not mean that little additional population growth is to be expected; global population is likely to increase by another 2 billion over the next few decades. (See Figure 7.1.) Nonetheless, the end of world population growth, while not imminent, is now on the horizon (Lutz et al. 2001).

Within the boundaries of the MA ecosystems, the cultivated system contains the greatest number of people (4.1 billion in 2000). The coastal system has the highest population density, at 170 people per square kilometer (see MA *Current State and Trends,* Table 5.1). Population growth over the period 1990–2000 has varied across ecosystems. The highest growth rate (18.5% net over the decade) occurred in drylands. The greatest increase in population density was found in the coastal zone, where population growth totaled 23.3 people per square kilometer over the decade. The cultivated systems witnessed the greatest total increase in population during the period—506 million additional people. (See MA *Current State and Trends,* Chapter 5.)

The recent decades of great demographic change have produced unprecedented demographic diversity across regions and countries (Cohen 2003). Substantial population increases are still expected in sub-Saharan Africa, South Asia, and the Middle East. In Europe and East Asia, growth has slowed or even stopped, and rapid aging has become a serious concern.

Traditional demographic groupings of countries are breaking down. In the United States, a high-income country, a doubling of population in the future is anticipated. Many developing countries, including China, Thailand, and North and South Korea, now have low fertility rates that until recently were found only in high-income countries. In 24 countries, mainly in Europe, fertility has fallen to very low levels—below an average of 1.5 births per woman—prompting serious concerns not only about aging but also about population decline.

Mortality and urbanization rates vary widely across countries as well. Life expectancies are substantially higher in high-income countries (about 75 years) than in developing ones (63 years), although the gap has closed from over 17 years of difference in the early 1970s to about 12 years today. Particular countries or regions have done much better, or worse, than the average: life expectancy in East Asia grew impressively over the past few decades, while improvements stalled in Russia and have been reversed in some parts of Africa (due primarily to the impact of HIV/AIDS).

**Table 7.1 Global Population Trends since 1950** (United Nations 2003d)

***Total population size***

| | 1950 | 1975 | 2000 |
|---|---|---|---|
| | | *(million)* | |
| Higher-income countries | 813 | 1,047 | 1,194 |
| Lower-income countries | 1,706 | 3,021 | 4,877 |
| Africa | 221 | 408 | 796 |
| Asia | 1,398 | 2,398 | 3,680 |
| Europe | 547 | 676 | 728 |
| Latin America and Caribbean | 167 | 322 | 520 |
| North America | 172 | 243 | 316 |
| Oceania | 13 | 22 | 31 |
| **World** | **2,519** | **4,068** | **6,071** |

***Life expectancy, both sexes combined***

| | 1950–55 | 1970–75 | 1995–2000 |
|---|---|---|---|
| | | *(years)* | |
| Higher-income countries | 66.1 | 71.4 | 74.8 |
| Lower-income countries | 41.0 | 54.7 | 62.5 |
| Africa | 37.8 | 46.2 | 50.0 |
| Asia | 41.4 | 56.3 | 65.7 |
| Europe | 65.6 | 71.0 | 73.2 |
| Latin America and Caribbean | 51.4 | 60.9 | 69.4 |
| North America | 68.8 | 71.6 | 76.4 |
| Oceania | 60.3 | 65.8 | 73.2 |
| **World** | **46.5** | **58.0** | **64.6** |

***Population growth rate per year***

| | 1950–55 | 1970–75 | 1995–2000 |
|---|---|---|---|
| | | *(percent)* | |
| Higher-income countries | 1.20 | 0.78 | 0.34 |
| Lower-income countries | 2.08 | 2.36 | 1.61 |
| Africa | 2.19 | 2.66 | 2.35 |
| Asia | 1.95 | 2.24 | 1.41 |
| Europe | 0.99 | 0.59 | 0.02 |
| Latin America and Caribbean | 2.65 | 2.45 | 1.56 |
| North America | 1.71 | 0.97 | 1.07 |
| Oceania | 2.15 | 2.07 | 1.41 |
| **World** | **1.80** | **1.94** | **1.35** |

***Total fertility rate***

| | 1950–55 | 1970–75 | 1995–2000 |
|---|---|---|---|
| | | *(fertility rate)* | |
| Higher-income countries | 2.84 | 2.13 | 1.58 |
| Lower-income countries | 6.16 | 5.42 | 3.11 |
| Africa | 6.74 | 6.71 | 5.22 |
| Asia | 5.89 | 5.06 | 2.72 |
| Europe | 2.66 | 2.16 | 1.42 |
| Latin America and Caribbean | 5.89 | 5.03 | 2.72 |
| North America | 3.47 | 2.01 | 2.01 |
| Oceania | 3.90 | 3.25 | 2.45 |
| **World** | **5.02** | **4.48** | **2.83** |

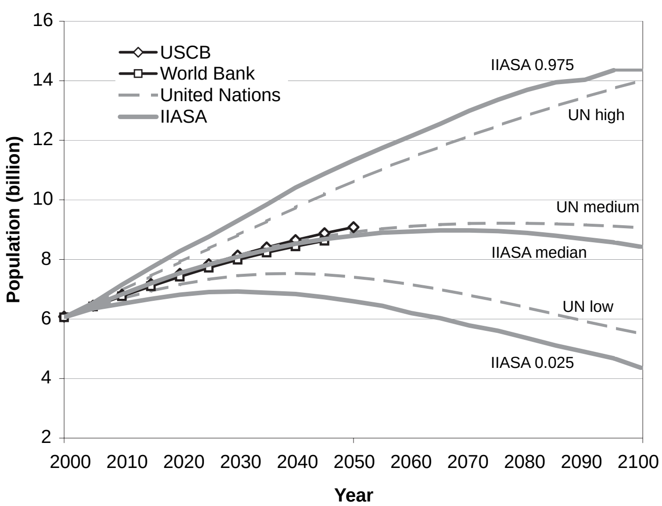


**Figure 7.1. Global Population Projections, 2005–2100** (Lutz et al. 2001; United Nations 2003c; United States Census Bureau 2003; World Bank 2003)

Regions are also distinguished by different urbanization levels. High-income countries typically have populations that are 70–80% urban. Some developing-country regions, such as parts of Asia, are still largely rural, while Latin America, at 75% urban, is indistinguishable from high-income countries in this regard. Within the MA system boundaries, the coastal zone has the highest urbanization rate, at 64% (see MA *Current State and Trends,* Chapter 27; see also the discussion of urbanization in the land conversion section later in this chapter).

The diversity of current conditions means that the outlook for future demographic change is highly variable as well. Current age structures are a key determinant of population growth over the next few decades, due to the ''momentum'' inherent in young populations. Thus, currently high-fertility regions with young age structures (sub-Saharan Africa, Middle East, and South Asia) have some population growth built in. In contrast, the very low fertility and relatively old age structures of some European countries have generated ''negative momentum,'' a built-in tendency for the population to decline even if fertility rises in the future (Lutz et al. 2003).

Differences in urbanization, education, economic and social conditions (especially for women), and other determinants of fertility change are also major factors in the outlook for future demographic changes, and vary widely. As a result, growth over the next several decades is expected to be concentrated in particular sub-populations, especially the poorest, urban communities in developing countries. In addition, while substantial population aging is expected in all regions during the century, there will be strong differences in timing and degree. The lowest fertility high-income countries are already aging and will lead the transition to relatively old age structures, but in some developing countries such as China, which saw sharp declines in fertility over the past few decades, aging is expected to proceed more quickly.

#### *7.2.1.2 Determinants of Fertility, Mortality, and Migration*

Since the 1940s, demographers have projected future changes in population size and composition by age and sex using the cohort component method, which involves first projecting trends in the components of population change: fertility, mortality, and migration. Trends in these variables are themselves influenced by a wide range of social, economic, and cultural factors. This section briefly sketches the principal determinants for each component.

##### *7.2.1.2.1 Fertility*

The conceptual basis for projecting future fertility changes in a country differs, depending on its current level of fertility. Unless otherwise indicated, what is meant by ''fertility'' is the period total fertility rate. The TFR is defined as the number of children a woman would give birth to if through her lifetime she experienced the set of age-specific fertility rates currently observed. Since age-specific rates generally change over time, TFR does not in general give the actual number of births a woman alive today can be expected to have. Rather, it is a synthetic index meant to measure age-specific birth rates in a given year.

In those countries with high fertility—defined here as fertility above the ''replacement level'' of slightly more than two births per woman—demographic transition theory provides the primary basis for forecasting fertility trends. The concept of demographic transition is a generalization of events observed over the past two centuries in those countries with the highest incomes today. While different societies experienced the transition in different ways, in general these societies have gradually shifted from small, slowly growing populations with high mortality and high fertility to large, slowly growing populations with low mortality and low fertility (Knodel and Walle 1979; van de Kaa 1996; Lee 2003). During the transition itself, population growth accelerates because the decline in death rates precedes the decline in birth rates, creating a sudden ''surplus'' of births over deaths.

Evidence from all parts of the world overwhelmingly confirms the relevance of the concept of demographic transition. The transition is well advanced in all developing countries, except in sub-Saharan Africa, and even there the beginnings of a fertility decline have become apparent (Cohen 1998a; Garenne and Joseph 2002). Fertility is already at or below replacement level in several developing countries, including China.

The idea that reduced demand for children drives fertility decline was given theoretical rigor in the 1960s with the development of a theory based on changes in determinants of parents' demand for children (Becker 1960; Becker and Lewis 1973; Becker and Barro 1988). The model assumes that fertility falls because, as economic development proceeds, parents' preferences shift toward higher ''quality'' children requiring greater investments in education and health, while increases in women's labor force participation and wages increase the opportunity costs of raising children. At the same time, development leads to a decline in some of the economic benefits parents may derive from children, such as household labor, income, and old age security. Thus, as the net cost of children rises, demand falls.

While an important advance in understanding fertility behavior, this framework by itself is insufficient to explain the diversity of observed fertility change. It has been extended and made more flexible by taking into account sociological aspects such as the effects of development on attitudes toward fertility regulation (Easterlin 1969, 1975), the importance of education and social change in changing women's childbearing desires and their ability to achieve them, changes in cultural contexts such as a decline in religious beliefs and increased materialism (Lesthaeghe 1983; Ryder 1983), and shifts away from extended family structures toward the child-centered nuclear family (Caldwell 1982). Many researchers have also emphasized the importance of the spread of new ideas in general, and in particular those regarding the feasibility and acceptability of birth control (Cleland and Wilson 1987; Bongaarts and Watkins 1996).

Population-related policies have clearly played a role in the decline of fertility in developing countries over the past several decades and are likely to be one determinant of future fertility. For example, it is widely acknowledged that China's population policy played a central role in its very rapid decline in fertility in the 1970s and in maintaining China's currently low fertility. Future changes to its one-child policy could affect fertility trends over the coming decades, although this link should not be considered automatic (Wong 2001).

Family planning programs in many parts of the world have been aimed at meeting ''unmet need'' for contraception by helping couples overcome obstacles (social and cultural, as well as economic) to contraceptive use (Bongaarts 1994). Measuring the influence on fertility of family planning programs is difficult, but one estimate concluded that 43% of the fertility decline in developing countries between the early 1960s and late 1980s could be attributed to program interventions (Bongaarts 1997). Although family planning programs have been the main intervention to lower fertility, they have often been implemented concomitantly with general economic development programs, educational programs, and health programs, each of which may have an indirect effect on changing fertility. Future change in fertility may also be affected by public policies that address such social and economic factors as women's status, educational and employment opportunities, and public health, as called for by the Cairo Program of Action, an outcome of the 1994 International Conference on Population and Development in Cairo. Although these policies are not primarily motivated by their potential effect on demographic trends, achieving them would likely lead to lower fertility (and lower mortality).

While each perspective on the determinants of fertility and mortality change offers important insights, no single, simple theory explains the multifaceted history of demographic transition around the world. Each explanation suffers from its own shortcomings, and for each, exceptions can be found (Oppenheim-Mason 1997; Robinson 1997). It is probably best to think of fertility and mortality transitions as being driven by a combination of factors rather than a single cause, but determining the precise mix of factors at work in a particular population at a given time remains an elusive goal (Hirschman 1994; National Research Council 2000).

Demographic transition theory provides little guidance on future fertility trends in countries that have already completed the transition to low fertility. Traditionally, many population forecasters assumed that fertility in all countries would eventually stabilize at replacement level, leading to stabilization of population growth. This approach has been strongly criticized as assigning a magnetic force to ''replacement-level'' fertility, without any empirical evidence that total fertility rates will naturally drift to that level (Demeny 1997). Total fertility has been below replacement level in 20 European countries for at least two decades, and it is currently below 1.5 children per woman in 21 European countries (United Nations 2003a). Fertility has also fallen below replacement level in several developing countries. By 2000, 59 countries were below replacement level fertility, accounting for 45% of the world population (United Nations 2003a).

Many arguments support the idea that fertility will decline below replacement level in more populations in the future. These arguments can be grouped together under the term ''individuation,'' which encompasses the weakening of family ties, characterized by declining marriage rates and high divorce rates, the increasing independence and career orientation of women, and value shifts toward materialism and consumerism (Bumpass 1990). Individuation, together with increasing demands and personal expectations for the amount of attention, time, and money devoted to children, is likely to result in fewer couples who have more than one or two children and an increasing number of childless women.

While current trends and some plausible explanations may suggest that low fertility will continue, there is no compelling theory that can predict reproductive behavior in low-fertility societies. Although fertility typically continues to fall after reaching replacement level, there is no clear pattern to subsequent fertility trends. In some countries, fertility falls quickly to very low levels, while in others it has followed a more gradual slide. In the United States, Sweden, and some other countries, fertility declined well below replacement level and then rose nearly to replacement level again (and in Sweden, then returned again to low levels).

Some of these changes have been due to changes in the timing of births, even if the actual number of births women have over their lifetimes has changed little. Since the mean age of childbearing has been increasing in many high-income countries over the past several decades, part of the decline in TFR has been due to this timing effect and not to a change in the completed fertility of women (Bongaarts and Feeney 1998). Proposed explanations for the trend toward later childbearing include economic uncertainty for young adults, lack of affordable housing, increases in higher education enrollment rates, and difficulties women face in combining child raising with careers, including cultural factors and inflexible labor markets (Kohler et al. 2002).

Some demographers argue that the TFR is likely to increase in the future once the mean age of childbearing stops rising, as happened in the 1980s in the United States when fertility rose to its current, near-replacement level. An additional argument against continued very low fertility is that in surveys conducted in much of Europe, women consistently say they want about two children (Bongaarts 1999). There are many reasons why women may fail to reach this target (career plans, divorce, or infertility, for example), but this finding suggests that fertility is unlikely to remain extremely low, especially if societies make it easier for women to combine careers and childbearing. Nonetheless, it is unclear whether the younger women who are currently postponing births will recuperate this delayed fertility at older ages (Lesthaeghe and Willems 1999; Frejka and Calot 2001).

##### *7.2.1.2.2 Mortality*

Mortality decline as a component of the demographic transition has typically begun with reductions in infectious disease driven by improvements in public health and hygiene along with better nutrition as incomes rose and the impacts of famines reduced (Lee 2003). Reduced infant mortality, in particular, is a relatively straightforward consequence of public health and sanitation expenditures. Later, reductions in mortality are driven by reductions in chronic and degenerative diseases such as heart disease and cancer.

Mortality projections are based on projecting future life expectancy at birth—that is, the average number of years a child born today can expect to live if current age-specific mortality levels continued in the future. (Life expectancy—like the total fertility rate—measures the situation at a given period of time; it does not reflect the actual experience of an individual. Nonetheless, life expectancy provides a useful summary of the mortality rates for each age and sex group in a population at a particular time.)

Uncertainties about future changes in life expectancy are quite different in high- and low-mortality countries. In the latter, primarily in industrial regions, mortality is concentrated at old ages. The long-term outlook for life expectancy improvements depends mainly on whether or not a biological upper limit to life expectancy exists and, if it does, how soon it might be reached. Death rates have been declining steadily at old ages, but there is a range of opinions on how long this trend can continue.

One point of view is that life expectancy in higher-income countries is unlikely to increase much beyond 85 years from its current level of about 75 years. Some have argued that this age represents an intrinsic (genetically determined) limit to the human life span (DeFries et al. 2002). Reductions in mortality that do occur are likely to increase an individual's chances of surviving to the maximum life span but not extend the maximum itself. Others argue that while the intrinsic limit may be modifiable, in practical terms it is unlikely to be exceeded without unforeseeable medical breakthroughs (Olshansky et al. 1990; Olshansky et al. 2001). This view is based on calculations showing that increasing life expectancy to 85 years would require dramatic reductions in mortality rates, particularly among the elderly. Olshansky et al. point out that complete elimination of deaths from diseases such as heart disease, cancer, and diabetes—which account for a large proportion of deaths among the elderly—would not extend average life expectancy beyond 90. Only breakthroughs in controlling the fundamental rate of aging could do that.

Other researchers hold that reduced mortality among the oldest ages could produce substantial improvements in life expectancy. Data from several higher-income countries shows that death rates at old ages have been falling over the past several decades, and this improvement has been accelerating, not decelerating, as would be expected if a limit were being approached (Vaupel 1997; Oeppen and Vaupel 2002).

In most developing countries, possible limits to the life span are not as relevant to projections because life expectancies are lower and mortality is not as concentrated at the oldest ages. Future life expectancy will be determined by the efficiency of local health services, the spread of traditional diseases such as malaria and tuberculosis and of new diseases such as HIV/AIDS, as well as living standards and educational levels. Projecting mortality in developing countries is difficult because of the relative scarcity and poor quality of data on current and past trends. In addition, the future course of the HIV/AIDS epidemic could substantially affect mortality in many countries, especially in sub-Saharan Africa where HIV prevalence rates are especially high. HIV/AIDS has slowed, and in some cases reversed, the impressive gains in life expectancy in developing countries over the past several decades. In Botswana, for example, life expectancy has dropped from about 65 years in the early 1990s to 56 years in the late 1990s and is expected to decline to below 40 years by 2005 (United Nations 2003e).

The possibility of environmental feedbacks is sometimes suggested as important when considering future mortality rates. The most frequently discussed possibilities for future effects center around the idea of carrying capacity (the maximum number of people that Earth can support) and the potential health impacts of climate change. Currently, however, population projections do not take explicit account of possible large-scale environmental feedbacks on mortality that have not yet occurred, although they do implicitly consider smaller effects, since they have affected average trends in the past, and since past trends serve as an important component of projections (National Research Council 2000).

There are at least three reasons that carrying capacity is not considered in long-term population projections. First, there is no agreement on what the limiting factors to population growth might be. Carrying capacity is contingent on economic structure, consumption patterns, preferences (including those regarding the environment), and their evolution over time (Arrow et al. 1995), defying attempts to attach a single number to the concept. Any proposed limit relevant to projections over the next century or two would depend primarily on which factor or factors were assumed to be limiting, as well as on how thinly any one factor had to be spread to begin to exert its limiting influence. Proposed limits have been based on a wide range of factors, including supplies of energy, food, water, and mineral resources, as well as disease and biological diversity. No consensus on the human carrying capacity has emerged; on the contrary, the range of estimates has widened over time (Cohen 1995). Second, even if the relevant factors could be agreed on, it would be difficult to project the future evolution of those factors for use in population projections (Keyfitz 1982). Future agricultural systems, energy supplies, and water availability are difficult to foresee in their own right, and there is no consensus in these areas to which demographers might turn. Third, even if these factors could be reliably predicted, their effects are mediated through economic, political, and cultural systems in ways that are not possible to quantify with confidence (Cohen 1998b).

Environmental effects on mortality short of a large-scale catastrophe have received increasing attention, especially those that might be driven by future climate change, particularly in combination with other trends such as changing spatial distributions of population, land use change, and agricultural intensification. The ultimate mortality impact of these environmental health risks is uncertain (Daily and Ehrlich 1996). (See Chapter 9 of IPCC (2002) for a discussion of climate change and human health, and Chapter 11 in this volume.) Yet even the most pessimistic forecasts for additional deaths, when spread over large populations, do not significantly change the general outlook for mortality globally.

#### *7.2.1.2.3 International migration*

Future international migration is more difficult to project than fertility or mortality. Migration flows often reflect short-term changes in economic, social, or political factors, which are impossible to predict. And since no single, compelling theory of migration exists, projections are generally based on past trends and current policies, which may not be relevant in the future. Even past migration flows provide minimal guidance because there is often little information about them.

Projections of international migration generally begin with consideration of current and historical trends (Zlotnik 1998; United Nations 2003b). For example, most projections foresee continued net migration into traditional receiving countries such as the United States, Canada, and Australia. These trends may then be modified based on potential changes in underlying forces affecting migration. The forces are complex, and no single factor can explain the history of observed migration trends. For example, population growth rates in sending regions are not a good indicator of emigration flows. In general, correlations between rates of natural increase in developing countries and levels of emigration to higher-income countries have been weak or nonexistent.

A number of theories from different disciplines have attempted to explain migration flows (Massey et al. 1998). International migration is often viewed mainly as a mechanism for redistributing labor to where it is most productive (Todaro 1976), driven by differences in wages among areas. Individuals decide whether to migrate by weighing the estimated benefits of higher wages in a new location against the costs of moving. The choice of destination will depend on where migrants perceive their skills to be most valuable.

This basic model emphasizing the labor market has been extended to address recognized shortcomings. The newer approach, sometimes called new economics models, assumes that migration decisions are not strictly individual but are affected by the preferences and constraints of families. Decisions are made not only to maximize income, for example, but also to meet family or household demands for insurance. By diversifying family labor, households can minimize risks to their well-being (Stark 1991).

Migration theory also requires consideration of political factors, especially to explain why international flows are much lower than would be predicted based solely on economic costs and benefits. Since a fundamental function of the state is to preserve the integrity of a society by controlling entry of foreigners, explanations must balance the interests of the individual with those of society as expressed through migration policies.

The various factors influencing migration decisions are often categorized according to whether they attract migrants to a region of destination (''pull'' factors), drive migrants out of regions of origin (''push'' factors), or facilitate the process of migration (''network'' factors) (Martin and Widgren 1996). In addition to the factors evoked by these theories, others might include the need to flee life-threatening situations, the existence of kin or other social networks in destination countries, the existence of an underground market in migration, and income inequality and changes in cultural perceptions of migration in sending countries that are induced by migration itself (United Nations 1998).

An additional factor particularly relevant to the MA is the potential for growing numbers of ''environmental refugees''—people driven to migrate by environmental factors (El-Hinnawi 1985). There is considerable debate on the relevance of environmental change to migration (Suhrke 1994; Hugo 1996). At one end is the view that environmental conditions are just one of many ''push'' factors influencing migration decisions (MacKellar et al. 1998). Environmental change, in this view, primarily acts indirectly by reducing income (by, for example, reducing agricultural productivity), making income less stable or negatively affecting health or environmental amenities. It also acts in concert with other factors, and therefore its relative role is difficult to isolate. At the other end lies the view that deteriorating environmental conditions are a key cause of a significant number of migrants in developing countries (Jacobson 1989; Myers 2002). While other factors such as poverty and population growth may interact with environmental change, environmental degradation is assumed to play a principal role.

The degree to which environmental migration is relevant to long-term population projections depends in part on the anticipated magnitude of the population movements. One estimate puts the number of environmental refugees in the mid-1990s at 25 million (over half of them in sub-Saharan Africa) (Myers and Kent 1995; Myers 2002). In comparison, there were about 26 million refugees as traditionally defined and an estimated 125 million international migrants—that is, people living in a country other than the one in which they were born (Martin and Widgren 1996; United Nations 1998). According to the United Nations High Commissioner on Refugees, there were about 13 million refugees in 1995, and an additional 13 million ''persons of concern to the UNHCR,'' a group that includes people forced from their homes or communities but still residing in their own countries. Since Myers includes displaced persons who have not crossed international borders in his definition of ''environmental refugees,'' the total figure—26 million—is the most relevant for comparison. Myers (2002) predicts that the number of environmental refugees is likely to double by 2010, and could swell to 200 million by 2025 due to the impacts of climate change and other sources of environmental pressure.

The potential relevance of these figures to population projections also depends on the level of aggregation. Most environmental migration occurs within national boundaries and therefore would not affect any of the long-term population projections. Additionally, some long-term projections are made at the level of world regions, so that much of the international migration would be masked as well. Finally, if environmental migration occurs in the future, its relevance compared with other factors driving migration, such as economic imbalances, must be weighed before concluding it is important to long-range population projections.

#### *7.2.1.3 Demographic Change and Ecosystem Consequences*

The ways in which population change influences ecosystems are complex. The basic pathway is from growing consumption driven by population to production processes that rely in part on ecosystem services to meet that consumption. The ultimate effects on ecosystems of an additional person are influenced by the entire range of indirect drivers. Research on direct population-environment interactions has focused increasingly on demographic characteristics that go beyond population size, and on a wide range of mediating factors.

For example, the energy studies literature has identified household characteristics such as size, age, and composition as key determinants of residential energy demand (Schipper 1996a). Household size appears to have an important effect on per capita consumption, most likely due to the existence of substantial economies of scale in energy use at the household level (Ironmonger et al. 1995; Vringer and Blok 1995; O'Neill and Chen 2002). Smaller household size is often accompanied by a larger number of households, and there is some evidence that the number of households, rather than population size per se, drives environmentally significant consumption (Cramer 1997, 1998). Research on ecological impacts of changes in household size and numbers has a shorter history but has also suggested a link between the two (Liu et al. 2003). Much of this literature is based on case studies, which suggest the importance of local context in determining population and land use interactions (National Academy of Sciences 2001). It has also been suggested that larger populations create difficulties for democratic institutions and thus environmental governance (Dahl and Tufte 1973; Frey and Al-Mansour 1995; Dietz 1996/1997).

These relationships may be important determinants of aggregate consumption in the future, since the proportion of the population living in various household types may shift substantially. The aging process itself leads to a shift toward smaller households, as children become a smaller fraction of the population. In addition, changes in preferences for nuclear over extended households may lead to even greater shifts in developing countries.

#### *7.2.1.4 Overview of Demographic Drivers in the MA Scenarios*

Four population projections were developed for the MA Scenarios Working Group to use in the quantification of storylines. All four projections are based on the IIASA 2001 probabilistic projections for the world (Lutz et al. 2001), but they are designed to be consistent with the four MA storylines, as judged by the Working Group with additional input from IIASA demographers (O'Neill 2005).

Table 7.2 lists the qualitative assumptions about fertility, mortality, and migration for each storyline. These assumptions are expressed in terms of high, medium, and low (H/M/L) categories, defined not in absolute but in relative terms—that is, a high fertility assumption for a given region means that fertility is assumed to be high relative to the median of the probability distribution for future fertility in the IIASA projections. Since the storylines describe events unfolding through 2050, the demographic assumptions specified here apply through 2050 as well. For the period 2050–2100, the demographic assumptions were assumed to remain the same, in order to gauge the consequences of trends through 2050 for the longer term. This is not intended to reflect any judgment regarding the plausibility of trends beyond 2050.

Figure 7.2 shows results for global population size. The range of population values in the scenarios is 8.1–9.6 billion in 2050 and 6.8–10.5 billion in 2100. These ranges cover 50–60% of the full uncertainty distribution for population

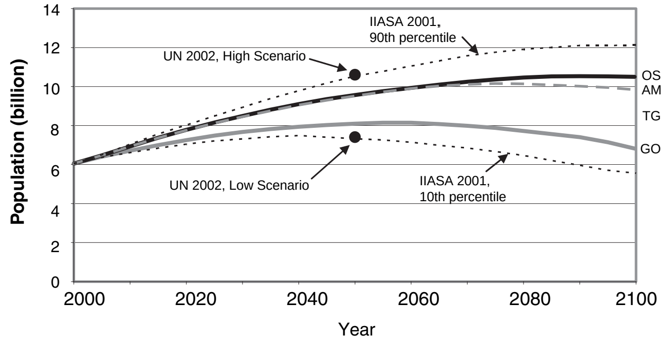


**Figure 7.2. MA World Population Scenarios, 2000–2100.** OS: Order from Strength, TG: TechnoGarden, AM: Adapting Mosaic, GO: Global Orchestration. An overview of each scenario can be found in the Summary.

size in the IIASA projections. The primary reason that these scenarios do not fall closer to the extremes of the full uncertainty distribution is that they correlate fertility and mortality: the Order from Strength scenario generally assumes high fertility and high mortality, and the Global Orchestration scenario generally assumes low fertility and low mortality. Both of these pairs of assumptions lead to more moderate population size outcomes.

### 7.2.2 *Economic Drivers: Consumption, Production, and Globalization*

Economic activity is a consequence of humans striving to improve their well-being. It is the myriad of technological processes that combine physical inputs, many derived from ecosystems, with human effort to generate goods and services that can improve human well-being. This activity is influenced by the endowment of natural resources, including ecosystem services (natural capital), the number and skills of humans (human capital), the stock of built resources (manufactured capital), and the nature of human institutions, both formal and informal (social capital). An early definition of social capital was ''features of social organization, such as trust, norms, and networks that can improve the efficiency of society by facilitating coordinated actions'' (Putnam et al. 1993, p 167). We expand the definition here to include formal institutions, such as the various levels of

**Table 7.2 Fertility, Mortality, and Migration Assumptions, by Scenario**[a]

| Variable | Global Orchestration | TechnoGarden | Order from Strength | Adapting Mosaic |
|---|---|---|---|---|
| Fertility | HF: low<br>LF: low<br>VLF: medium | HF: medium<br>LF: medium<br>VLF: medium | HF: high<br>LF: high<br>VLF: low | Order from Strength until 2010, deviate to medium by 2050 |
| Mortality | D: low<br>I: low | D: medium<br>I: medium | D: high<br>I: high | Order from Strength until 2010, deviate to medium by 2050 |
| Migration | high | medium | low | low |

Key: I = more-developed country regions, D = less-developed country regions, HF = high-fertility regions (TFR $>$ 2.1 in year 2000), LF = low-fertility regions (1.7 $<$ TFR $<$ 2.1), VLF = very-low-fertility regions (TFR $<$ 1.7).

Notes: [a]In the ITASA projections, migration is assumed to be zero beyond 2070, so all scenarios have zero migration in the long run.

governments and their policies and regulations, and cultural and religious aspects of social organization.

Economic activity is also strongly influenced by available technologies. Local resource endowments of all kinds, and technologies, can be enhanced by access to other markets. International flows of goods and services, capital, labor, and ideas change the mix of economic activities that can be undertaken at home and the variety of items available for consumption.

#### *7.2.2.1 Economic Growth, Changing Consumption Patterns, and Structural Transformation*

Human well-being is clearly affected by economic growth and its distribution. Income received by individuals and families determines their level and nature of consumption. As per capita income grows, the nature of consumption changes, shifting from basic needs to goods and services that improve the quality of life. Businesses respond to these changing demands by producing an evolving mix of products.

As income increases, the mix of economic activities changes. This process, sometimes referred to as structural transformation, is driven by human behavior summarized in the form of two related economic ''laws'' with important consequences for ecosystems—Engel's law and Bennett's law. Engel's law, named after the German statistician who first observed the resulting statistical regularity, states that as income grows, the share of additional income spent on food declines. This relationship follows from basic human behavior. After basic food needs are met, the demand for an additional quantity of food drops off rapidly. Bennett's law states that as incomes rise, the source of calories changes. (A monograph by M. K. Bennett on Wheat in National Diets in a 1941 issue of *Wheat Studies* (Bennett 1941) and related comparative studies of the consumption of staple foods led to the empirical generalization that there is an inverse relationship between the percentage of total calories derived from cereals and other staple foods and per capita income.) The importance of starchy staples (e.g. rice, wheat, potatoes) declines, and diets include more fat, meat and fish, and fruits and vegetables. This behavior is the result of a general human desire for more dietary diversity and the ability to afford it as income rises.

These laws have several consequences for ecosystem condition and demand for ecosystem services. As income grows, the demand for nonagricultural goods and services increases more than proportionally. Producers respond by devoting relatively more resources to industry and service activities than agriculture. The share of agricultural output in total economic activity falls. The shift to a more diverse diet, in particular to more animal- and fish-based protein intake, slows the shift away from agriculture. Total consumption of starchy staples rises over some range of incomes as animal consumption that relies on feed grains gradually replaces direct human consumption of those grains. Eventually the demand for more diverse diets is satisfied, and further income growth is spent almost entirely on nonagricultural goods and services.

Industrial output share rises initially but then falls. Throughout the process of economic development, the importance of services in economic output rises continuously. A consequence of this shift toward services is that by the late 1990s, services provided more than 60% of global output, and in many countries an even larger share of employment (World Trade Organization 2004). In 2000, agriculture accounted for 5% of world GDP, industry accounted for 31%, and service industries, 64% (World Resources Institute et al. 2002).

Figure 7.3 documents the shift in economic structure in the past two centuries of the world's largest economies from agricultural production to industry and, to a greater extent, services. In developing regions a marked decline in the contribution of agriculture to GDP has occurred in recent years, but the contribution of services is larger than it was historically in industrial countries at the same level of income.

The shift away from agriculture and toward nonagricultural goods and then services is sometimes viewed as a process that ultimately reduces pressures on ecosystems, since services are assumed to be the least demanding of ecosystem products. But this outcome must be interpreted carefully. It is important to distinguish between absolute and relative changes. High-income countries almost always produce more agricultural output than when they were poor, but industrial and services output grows much faster, so the relative contribution of agriculture declines. Technological change further replaces most of the labor force in agriculture, potentially altering the demands for ecosystem services. The way agricultural statistics are reported also tends to overemphasize the extent of the decline in the economic importance of agriculture. In developing countries, the agricultural sector is ''vertically integrated''—farmers produce everything from seeds and agricultural infrastructure to food services. In high-income countries, ''agricultural'' statistics focuses only on production of primary products. ''Food'' production is reported in statistics on industry, transport, and services (fast food, restaurants, and so on).

Urbanization also influences the structure of food consumption, increasing the service content dramatically. Rural consumers are more likely to consume food produced at home. Urban consumers are more likely to demand easily prepared, quick meals and to purchase them from restaurants. Supermarkets replace neighborhood stores and street vendors.

A few examples from Asian countries with rapidly rising incomes illustrate these phenomena, although similar changes are occurring throughout the developing world today and happened in the industrial world in the twentieth century. Data from China show that the human intake of cereals and the consumption of coarse grains decreased during the past two decades in both urban and rural populations, and there was a dramatic increase in the consumption of animal foods. A similar, but less dramatic change is also observed in India, with figures that suggest a doubling in the intake of fat calories over a 20-year period. Although the Indian consumption of rice and wheat has been increasing, the percentage of all cereals in household expenditure

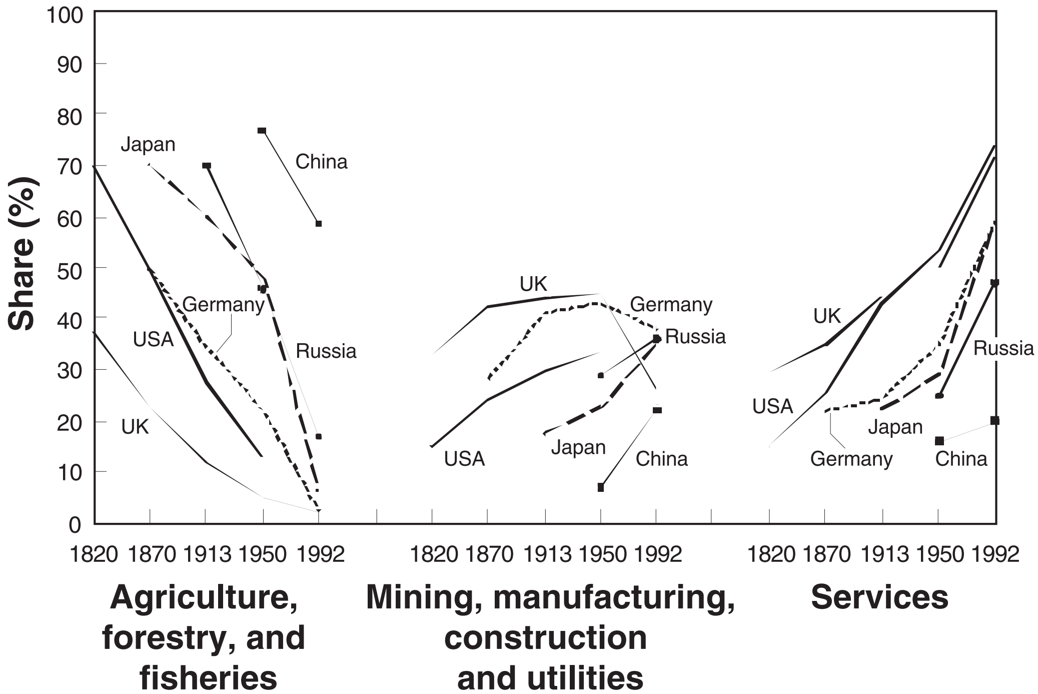


**Figure 7.3. Changes in Economic Structure for Selected Countries, 1820–1992** (Nakićenović et al. 2000; Maddison 1995)

has been declining. Meat consumption in India has been growing, although not as fast as in China (FAO 2004). The major increases in food consumption in India are in milk, eggs, fruit, and vegetables. Vegetable oil demand is also growing (USDA 2001).

By 2002, the share of supermarkets in the processed and packaged food retail market was 33% in Southeast Asia and 63% in East Asia. The share of supermarkets in fresh foods was roughly 15–20% in Southeast Asia and 30% in East Asia outside China. The 2001 supermarket share of Chinese urban food markets was 48%, up from 30% in 1999. Supermarkets are also becoming an emerging force in South Asia, particularly in urban India since the mid-1990s (Pingali and Khwaja in press).

#### *7.2.2.2 Economic Growth, Distribution, and Globalization*

The rate of growth and its sectoral composition depend on resource endowments, including ecosystem condition, on the technologies available, and on the extent of market reach. Hence the effects of global economic performance on ecosystems are more than straightforward changes in national income. International trade, capital flows, technology transfer, and technical change are crucial elements in global growth.

Perhaps the most comprehensive compilation of data on historical economic development is that of Maddison (1995). Table 7.3 shows Maddison's per capita GDP growth rate estimates for selected regions and time periods. Since 1820, global GDP has increased by a factor of 40, or at a rate of about 2.2% per year. In the past 110 years, global per capita GDP grew by a factor of more than five, or at a rate of 1.5% per year. Between 1950 and 2000, world GDP grew by 3.85%, resulting in an average per capita income growth rate of 2.09% for that period (Maddison 2003).

In the late twentieth century, income was distributed unevenly both within countries and around the world. (See Figure 7.4.) The level of per capita income was highest in North America, Western Europe, Australasia, and Northeast Asia (see Figure 7.5 in Appendix A), but growth rates were highest in South Asia, China, and parts of South America (see Figures 7.6a and 7.6b in Appendix A). If these trends continue, global income disparities will be reduced, although national disparities might increase. Africa is a conspicuous exception to the trend of growing incomes.

Economic growth is facilitated by trade. Growth in international trade flows has exceeded growth in global production for many years, and the differential may be growing. (See Figure 7.7.) In 2001, international trade in goods was equal to 40% of gross world product (World Bank 2003). Growth in trade of manufactured goods has been much more rapid than trade in agricultural or mining products. (See Figure 7.8.)

High incomes in OECD countries and rapid growth in income in some lower-income countries, combined with unprecedented growth of global interconnectedness, is leading to dramatic changes in lifestyles and consumption patterns. For example, tourism is one of the most rapidly growing industries, and growth in trade of processed food products and fresh fruits and vegetables is much more rapid than growth in trade of raw agricultural commodities.

Economic growth requires an expansion of physical and institutional infrastructure. The development of this infrastructure can play a major role in the impacts on ecosystems. In a review of 152 studies of tropical deforestation, Geist and Lambin (2002) found that 72 studies cited infrastructure extension (including transportation, markets, settlements, public services, and private-sector activities) as an important direct driver. In a similar study evaluating 132

**Table 7.3 Per Capita GDP Growth Rates for Selected Regions and Time Periods** (Nakićenović et al. 2000, based on Maddison 1995, with 1990–2000 data from Maddison 2003)

| | 1870–1913 | 1913–50 | 1950–80 | 1980–92 | 1990–2000 |
|---|---|---|---|---|---|
| | | | *(percent per year)* | | |
| Western Europe | 1.3 | 0.9 | 3.5 | 1.7 | 1.7 |
| Australia, Canada, New Zealand, United States | 1.8 | 1.6 | 2.2 | 1.3 | 1.9 |
| Eastern Europe | 1.0 | 1.2 | 2.9 | –2.4 | 0.6 |
| Latin America | 1.5 | 1.5 | 2.5 | –0.6 | 1.4 |
| Asia | 0.6 | 0.1 | 3.5 | 3.6 | 3.2 |
| Africa | 0.5 | 1.0 | 1.8 | –0.8 | 0.1 |
| **World (sample of 199 countries)** | **1.3** | **0.9** | **2.5** | **1.1** | **1.5** |

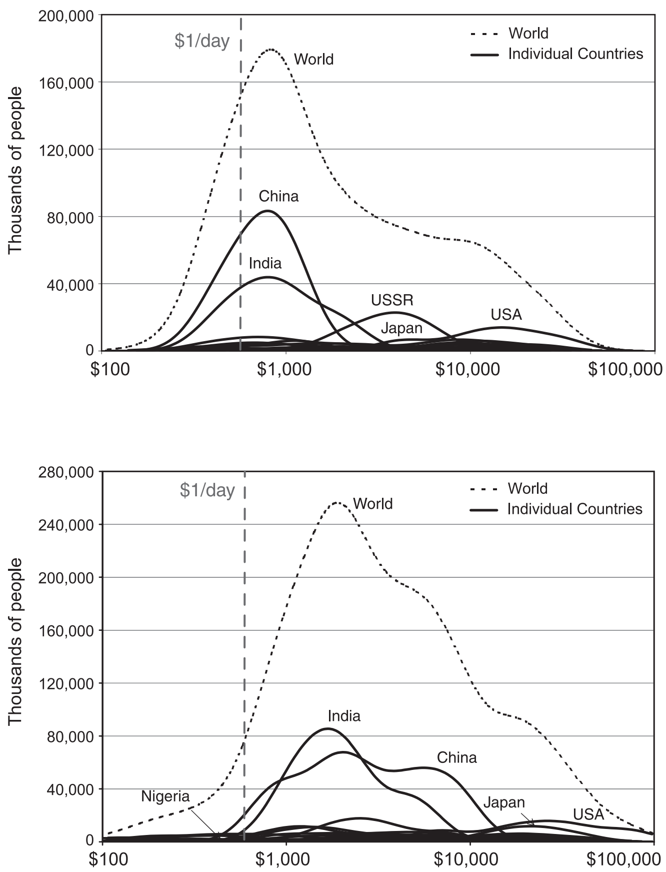


**Figure 7.4. Income Level and Distribution, 1970 and 2000.** Note: the data used are adjusted to 1985 prices and are PPP adjusted, drawing on various Summers and Heston/Penn-World Tables work. (Sala-i-Martin 2003, as reproduced in Barro and Sala-i-Martin 2003)

studies on desertification, they found infrastructure extension cited 73 times (Geist and Lambin 2004).

#### *7.2.2.3 Economic Distortions*

Government policies can alter market outcomes, increasing or reducing prices and changing production and consumption levels. By some estimates, distortions in agricultural markets are the largest. Total support to agriculture in OECD countries averaged over $324 billion per year in 2001–03; about three quarters of this amount was used to

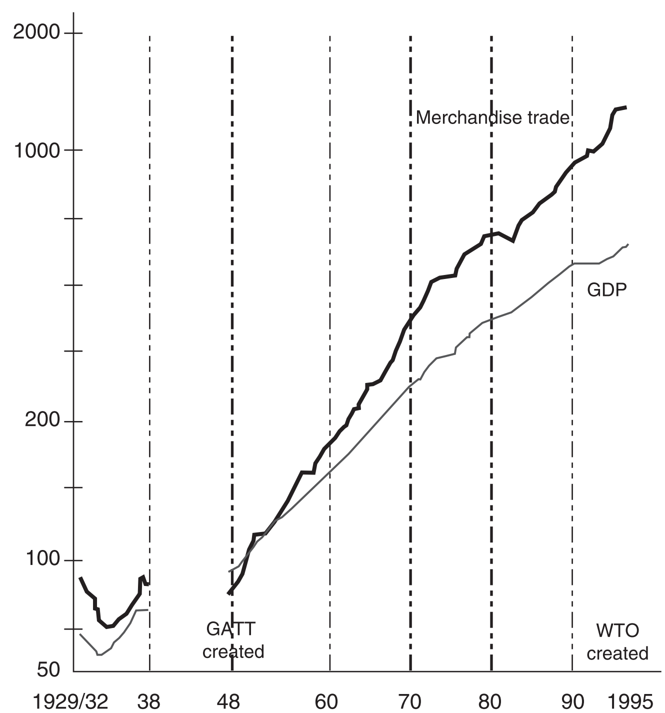


**Figure 7.7. World Trade and GDP Growth, 1930–95** (World Trade Organization 2003)

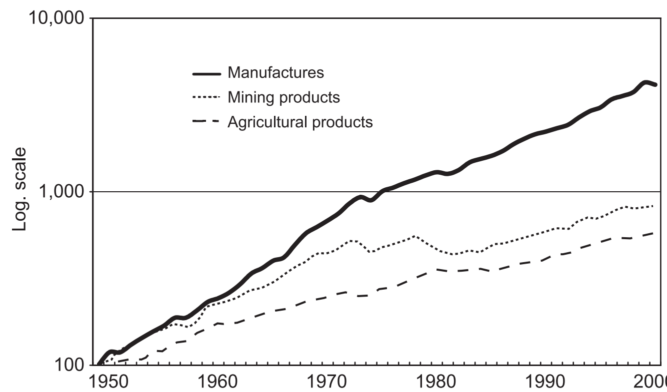


**Figure 7.8. World Merchandise Trade by Major Trade Groups, 1950–2001** (http://www.wto.org/English/res_e/statis_e/its2002_e/its02_longterm_e.htm)

support farm income directly, while the remainder went into general infrastructure improvements, research, marketing, and so on (OECD 2004). Many of these subsidies were in the form of higher prices to farmers, providing direct incentive to increase agricultural production. In low-income countries, on the other hand, governments sometimes tax agriculture directly or indirectly and do not provide support systems of research, marketing, and transportation infrastructure (Anderson and Hayami 1986).

According to the U.N. Environment Programme (UNEP 1999), global energy subsidies currently total $200 billion a year (de Moor 2002). OECD countries spend some $82 billion a year subsidizing energy production, mostly through tax breaks, cheap provision of public infrastructure and services, subsidized capital, and price support (OECD 1997). Globally, more than 80% of the subsidies are for fossil fuels use, among the most polluting energy sources.

#### *7.2.2.4 Determinants of Economic Growth and Development*

Economic growth and development depend on growth in the availability of resources, the mobility of those resources, the efficiency of their use, and the institutional and policy environment. Growth in per capita output depends on total output growing more rapidly than population.[1]

Numerous preconditions must be met before any "take off" into accelerated rates of productivity and economic growth can materialize. Research based on historical evidence allows a number of generalizations as to the patterns of advances in productivity and economic growth—the importance of economic openness to trade and capital flows and the contribution of technological change either through innovation or adoption. Little research has been undertaken on the role of ecosystems in economic growth.

Chenery et al. (1986) and Barro (1997) indicate strong empirical evidence of a positive relationship between trade openness and productivity, industrialization, and economic growth. For example, between 1990 and 1998 the 12 fastest-growing developing countries saw their exports of goods and services increase 14% and their output 8% (World Bank 2002). Dosi et al. (1990) highlight the critical roles of policies and institutions in realizing economic gains from the international division of labor.

It is theoretically possible that trade liberalization could have negative economic impacts on countries where property rights are not well defined, but little empirical evidence exists of this actually occurring. However, not all trade flows are equal in their effects on growth. Dollar and Collier (2001) found that the countries experiencing the most rapid trade-driven economic growth were trading a large share of high-technology products.

The late twentieth century trend toward more open economies led to greater uniformity in macroeconomic (monetary, fiscal, and exchange rate) policies across the world and facilitated capital mobility. International capital flows are critical to economic growth because they relieve resource constraints and often facilitate technology transfers that enhance productivity of existing resources. But not all developing countries participated equally. For instance, the vast majority of private-sector capital flows is concentrated in the 10 largest developing countries (World Bank 2002).

Adoption of technical improvements leads to the productivity growth essential to improvements in per capita income. Expenditures on research and development typically have high returns. Late-developing countries can, for a time, rely on borrowing technologies to improve productivity. Growth rates tend to be lower for economies at the technology and productivity frontier. For instance, nineteenth-century productivity and per capita GDP growth rates in the rapidly industrializing United States far exceeded those of England, then at the technology and productivity frontier. Likewise, in the post–World War II period, growth rates in Japan and most of Western Europe exceeded U.S. rates (by then at the technology and productivity frontier) (Maddison 1991, 1995). High human capital (education), a favorable institutional environment, free trade, and access to technology are key factors for rapid economic catch-up.

Sustained high-productivity growth and in some cases exploitation of natural resources (including ecosystem services) resulted in the current high levels of per capita income in OECD countries. Latecomers (such as Austria, Japan, and Scandinavia) rapidly caught up to the productivity frontier of other OECD economies in the post–World War II period. Per capita GDP growth rates of 3.5% per year were, for instance, achieved in Western Europe between 1950 and 1980. The developing economies of Asia achieved high per capita GDP growth rates beginning in the 1960s. Per capita GDP growth rates of individual countries have been extremely high for short periods—8% a year in Japan in 1950–73, 7% in Korea between 1965 and 1992, and over 6% per year in China from the early 1980s to the mid-2000s (Maddison 1995).

#### *7.2.2.5 Economic Productivity and Energy and Materials Intensity*

Economy activity requires energy and physical inputs, some of which are ecosystem services, to produce goods and services. The rate of conversion of inputs to economically valuable outputs is an important determinant of the impact on ecosystems. Materials and energy requirements (inputs) per unit of economic activity (often measured by GDP) are referred to as materials and energy intensity, respectively. Some evidence suggests that materials and energy intensity follow an inverted U-curve (IU hypothesis) as income grows—that is, the requirements per unit of economic activity rise for some earlier increases in economic activity and then decline. For some materials, the IU hypothesis (Moll 1989; Tilton 1990) holds quite well. The underlying explanatory factors are a mixture of structural change in the economy along with technology and resource substitution and innovation processes. Recent literature suggests that an N-shaped curve better describes the relationship of material intensity in high-income countries (De Bruyn and Opschoor 1994; De Bruyn et al. 1995; Suri and Chapman 1996; Ansuategi et al. 1997).[2]

Figure 7.9 in Appendix A shows material intensity versus per capita income data for 13 world regions for some metals (van Vuuren et al. 2000; see also the discussion in De Vries et al. 1994). Figure 7.10 in Appendix A shows a similar curve for total energy intensity (including traditional noncommercial energy forms) for 11 world regions, again as a function of per capita income (Nakićenović et al. 1998).

Commercial energy intensity of GDP generally follows the IU hypothesis, although the initially rising part of commercial energy intensity stems from replacing traditional energy forms and technologies with modern commercial energy forms. Traditional energy sources such as fuelwood; agricultural wastes, including dung; work of animals; wind mills; and water wheels have low energy intensity compared with modern energy sources such as oil products and electricity. The traditional methods of biomass combustion are not only inefficient but lead to a wide range of health hazards, such as indoor air pollution (Smith and Mehta 2003). Replacing traditional energy sources and carriers with modern sources increases the conversion efficiencies, especially at the point of end use. Consequently, the resulting aggregate total (commercial plus noncommercial) energy intensity shows a persistent declining trend over time, especially with rising incomes (Watson et al. 1996; Nakićenović et al. 1998). (See Figure 7.11 in Appendix A.)

There are two important points to retain from Figures 7.9–7.11 in Appendix A. First, energy and materials intensity (that is, energy use per unit of economic output) tend to decline with rising levels of GDP per capita. In other words, energy and material productivity—the inverse of energy intensity—improve in line with overall macroeconomic productivity.

Second, growth in productivity and intensity improvement has historically been outpaced by economic output growth. Hence, materials and energy use have risen in absolute terms over time (Nriagu 1996; Watson et al. 1996; Grübler 1998). An important issue for the future is whether technological advancement can outpace economic growth and lead to reductions in materials and energy use.

It is also important to emphasize that energy and material intensity are affected by many factors other than macroeconomic productivity growth. OECD (1998) notes that high rates of productivity increase have been associated in the past with new competitive pressures, strong price or regulatory incentives, catching up or recovery, and a good "climate for innovation." Table 7.4 summarizes selected macroeconomic, labor, energy, and material productivity increases that have been achieved in a range of economies and sectors at different times. (See also the discussion later on science and technology drivers.) This historical evidence suggests that continued productivity growth is a reasonable assumption for the future.

For instance, low historical rates of energy intensity improvement reflect the low priority placed on energy efficiency by most producers and users of technology. On average, energy costs account for only about 5% of GDP. Energy intensity reductions average about 1% per year, in contrast to improvements in labor productivity above 2% per year over the period 1870 to1992. Over shorter time periods, and given appropriate incentives, energy intensity improvement rates can be substantially higher, as in the OECD countries after 1973 or in China since 1977, where energy intensity improvement rates of 5% have been observed.

Rapid productivity growth can also occur during periods of successful economic catch-up; for instance, Japanese labor productivity grew at 7.7% annually during 1950–73 (Maddison 1995). Similar high-productivity growth was also achieved in industrial oil usage in the OECD or U.S. car fuel economies after 1973. Of the examples given in Table 7.4, productivity increases are the highest for communication. Many observers consider that communication may become as an important a driver of economic growth in the future as traditional resource- and energy-intensive industries have been in the past.

#### *7.2.2.6 Economic Drivers and Ecosystem Consequences*

The twin questions of the sustainability of economic growth and its impact on the environment were given high visibility by the 1987 report of the World Commission on Environment and Development (World Commission on Environment and Development 1987). Researchers have started to look for empirical evidence to answer these questions and provide a theoretical basis for understanding the interactions between economic development and environmental quality (Grossman 1995; Dasgupta et al. 1997).

Some argue that continuous economic growth requires an ever-increasing amount of resources and energy and produces rising pollution and waste levels. As Earth's natural resources and its capacity to absorb waste are finite, continuous economic growth will eventually overwhelm the carrying capacity of the planet (Georgescu-Roegen 1971 cited in Meadows et al. 1972; Panayotou 2000). Therefore, they argue, economic systems must eventually be transformed to steady-state economies, in which economic growth ceases (Daly 1991).

Others argue that economic growth results eventually in a strengthening of environmental protection measures and hence an increase in environmental quality. Higher per capita income levels spur demand for a better environment, which induces development of policies and regulations to address environmental quality problems. As the IU hypothesis suggests, initial empirical research found that at lower levels of income, economic growth is connected with increasing environmental damage. But after reaching a certain level of per capita income, the impact on at least some elements of environmental quality reverses.

Pollution abatement efforts appear to increase with income, a growing willingness to pay for a clean environment, and progress in the development of clean technology. This process seems well established for traditional pollutants, such as particulates and sulfur (e.g., World Bank 1992; Kato 1996; Viguier 1999), and there have been some claims that it might apply to greenhouse gas emissions. Schmalensee et al. (1998) found that $CO_2$ emissions have flattened and may have reversed for highly developed economies such as the United States and Japan. This IU relationship is sometimes referred to as the Environmental Kuznets Curve, named for a similar-looking relationship between income and inequality identified by Simon Kuznets (Kuznets 1955).

**Table 7.4 Examples of Productivity Growth for the Entire Economy and for Selected Sectors and Countries** (Nakićenović et al. 2000)

| Sector/Technology | Region | Productivity Indicator | Period | Annual Productivity Change (percent) |
|---|---|---|---|---|
| Whole economy [a] | 12 countries Europe | GDP/capita | 1870–1992 | 1.7 |
| Whole economy [a] | 12 countries Europe | GDP/hour worked | 1870–1992 | 2.2 |
| Whole economy [a] | U.S. | GDP/hour worked | 1870–1973 | 2.3 |
| Whole economy [a] | U.S. | GDP/hour worked | 1973–92 | 1.1 |
| Whole economy [a] | Japan | GDP/hour worked | 1950–73 | 7.7 |
| Whole economy [a] | South Korea | GDP/hour worked | 1950–92 | 4.6 |
| Whole economy [b] | World | GDP/primary energy | 1971–95 | 1.0 |
| Whole economy [b] | OECD | GDP/primary energy | 1971–95 | 1.3 |
| Whole economy [b] | U.S. | GDP/primary energy | 1800–1995 | 0.9 |
| Whole economy [b] | United Kingdom | GDP/primary energy | 1890–1995 | 0.9 |
| Whole economy [b] | China | GDP/primary energy | 1977–95 | 4.9 |
| Whole economy [c] | Japan | GDP/material use | 1975–94 | 2.0 |
| Whole economy [c] | U.S. | GDP/material use | 1975–94 | 2.5 |
| Agriculture [d,e] | Ireland | tons wheat/hectare | 1950–90 | 5.3 |
| Agriculture [e] | Japan | tons rice/hectare | 1950–96 | 2.2 |
| Agriculture [e] | India | tons rice/hectare | 1950–96 | 2.0 |
| Industry [a] | OECD (6 countries) | value added/hour worked | 1950-84 | 5.3 |
| Industry [a] | Japan | value added/hour worked | 1950–73 | 7.3 |
| Industry [b] | OECD | industrial production/energy | 1971–95 | 2.5 |
| Industry [b] | OECD | industrial production/energy | 1974–86 | 8.0 |
| New cars [f] | U.S. | vehicle fuel economy | 1972–82 | 7.0 |
| New cars [f] | U.S. | vehicle fuel economy | 1982–92 | 0.0 |
| Commercial aviation [g] | World | ton-km/energy | 1974–88 | 3.8 |
| Commercial aviation [g] | World | ton-km/energy | 1988–95 | 0.3 |
| Commercial aviation [g] | World | ton-km/labor | 1974–95 | 5.6 |
| Telephone call costs [d] | Transatlantic | London–NY, costs for 3 minutes | 1925–95 | 8.5 |
| Telephone cables [d] | Transatlantic | telephone calls/unit cable mass | 1914–94 | 25.0 |

Data sources: [a] Maddison 1995. [b] OECD and IEA statistics. [c] WRI 1997. [d] OECD 1998b; Waggoner 1996; Hayami and Ruttan 1985.
[e] FAO (various years 1963–96) Production Statistics. [f] Includes light trucks; Schipper 1996. [g] International Civil Aviation Organization statistics.

(See Grossman and Krueger 1992; Shafik and Bandyopadhay 1992; Panayotou 1993.)

The principal explanation for this relationship is changes in economic structure, from more industrial to more services, which occur with development and technical innovation that provides more resource-efficient technologies (Stern 2004). (While it often assumed that the shift toward services will reduce environmental impact, this assertion has been challenged (Salzman and Rejeski 2002; York et al. 2003b). In addition, a number of more indirect factors, such as the growing awareness of environmental problems, education, and improved environmental regulations, are now also seen as affecting the shape of the curve (Stern 2004).

The EKC hypothesis has generated many studies (for a thorough literature review, see Panayotou 2000 and Stern 2004). Stern (2004) provides one of the most recent reviews of the criticism and states that "there is little evidence for a common inverted U-shaped pathway which countries follow as their income rises." There are three main criticisms of the EKC results: First, its econometric foundations have been challenged (Harbaugh et al. 2000; Stern 2004). A second issue is the choice of indicators selected to represent environmental quality (Grossman 1995). A third criticism highlights omitted variables. Panayotou (2000) describes the use of per capita income in the EKC analysis as an "omnibus variable representing a variety of underlying influences." Urbanization, infrastructure, poverty, and income distribution are other factors in the complex interplay between economic growth, population, and environment (see, e.g., Rotmans and de Vries 1997; DeVries et al. 1999; O'Neill et al. 2001).

In summary, the EKC is at best a reduced form description, not a precise formulation of cause and effect, which captures a few of the complex interactions among economic activity and ecosystem condition and service. Other attempts at describing, identifying, and explaining aggregate relationships between economic activity and the environment, such as the ecological footprint (York et al. 2003a), are subject to similar criticisms.

In conclusion, there is controversy about whether the current rate of global economic growth is sustainable. There is little question that some, perhaps many, of the world's ecosystems have experienced unsustainable pressure as resources are extracted and ecosystem services are used to produce this growth. However, given the complexity of the interactions among economy and environment, simple formulations of the relationships between ecosystem sustainability and economic growth are not possible.

### *7.2.2.7 Tourism as an Example of Economic Drivers and the Environment*

Tourism provides a good example of the complexities of the interactions among economic growth and ecosystems. World tourism spending is expected to grow at over 6% per year (World Tourism Organization as referenced in Hawkins and Lamoureux 2001), making it one of the world's fastest growing industries and a major source of foreign exchange earning and employment for many developing countries.[3]

Tourism is increasingly focusing on natural environments. Specialty tourism, including ecotourism, accounted for about 20% of total international travel in the late 1990s (World Tourism Organization (1998) as cited in Hawkins and Lamoureux 2001). Ecotourism has the potential to contribute in a positive manner to socioeconomic well-being, but fast and uncontrolled growth can be the major cause of ecosystem degradation and loss of local identity and traditional cultures. Paradoxically, the very success of tourism can lead to the degradation of the natural environment. By drawing on local natural resources, tourism can reduce a location's attractiveness to tourists. The discussions in Weaver (2001) on tourism in rainforests, mountain ecosystems, polar environments, islands and coasts, deserts, and marine environments highlight these trade-offs.

Tourism is sometimes seen as an opportunity for economic development, economic diversification, and the growth of related activities, especially in developing countries. Among the benefits are direct revenues, generated by fees and taxes incurred and by voluntary payments for the use of biological resources. These revenues can be used for the maintenance of natural areas and a contribution of tourism to economic development, including linkage effects to other related sectors and job creation. However, it is well known that in developing countries a significant share of the initial tourist expenditures leave the destination country to pay for imported goods and services (Lindberg 2001).

Sustainable tourism can make positive improvements to biological diversity conservation, especially when local communities are directly involved with operators. If local communities receive income directly from a tourist enterprise, they are more likely to provide greater protection and conservation of local resources. Moreover, sustainable tourism can serve as an educational opportunity, increasing knowledge of and respect for natural ecosystems and biological resources. Other benefits include providing incentives to maintain traditional arts and crafts and traditional knowledge, plus innovations and practices that contribute to the sustainable use of biological diversity.

The impacts of tourism on ecosystems in general and on biodiversity in particular can be positive or negative, direct or indirect, and temporary or lasting, and they vary in scale from global to local (van der Duim and Caalders 2002). The different pathways these effects take are depicted in Figure 7.12.

Clearly, tourism acts on various direct drivers of the MA conceptual framework. Gössling (2002a) reports:

- Changes in land cover and land use due to tourism-related investments, including accommodation and golf courses, amount to more than 500,000 square kilometers, with the largest contribution coming from traffic infrastructure. Yet these numbers must be interpreted with caution, as roads, airports, and railways are used for nontourism activities also.
- Energy use and related carbon emissions occur due to transportation, but also due to accommodation and on-site activities. The overall contribution to carbon emissions is estimated to be on the order of 5%, of which transportation contributes about 90%.
- Biotic exchange is difficult to assess on a global scale, but various processes for exchange do exist. This includes the intentional or unintentional introduction of new species, both in the home and the hosting region. Extinction due to collection, hunting, or gathering of threatened species is another direct effect.
- Of indirect effect, yet from the human ecology perspective of high relevance, is the change of the human-nature relationships due to intercultural exchange during travel. Though it is believed that traveling can contribute to the increase in environmental consciousness of the guest, it is also possible that the people in the host country change their perception and understanding of the environment, for example by introducing the modern separation of "culture" and "nature" into indigenous societies (Gössling 2002b).

The potential adverse impacts of tourism can be roughly divided into environmental and socioeconomic, the latter often imposed on local and indigenous communities.

Direct use of natural resources, both renewable and nonrenewable, in the provision of tourist facilities is one of the most significant direct impacts of tourism in a given area. Land conversion for accommodation and infrastructure provision, the choice of the site, and the use of building materials are mechanisms by which ecosystems can be altered (Buckley 2001). Negative impacts on species composition and on wildlife can be caused by even such benign behavior as bird-watching (Sekercioglu 2002) and exacerbated by inappropriate behavior and unregulated tourism activities (such as off-road driving, plant-picking, hunting, shooting, fishing, and scuba diving). Tourist transportation can increase the risk of introducing alien species (waterborne pathogenic bacteria and protozoa, for instance) (Buckley 1998 as cited in Buckley 2001). And the manner and frequency of human presence can disturb the behavior of animals, as in the collapse of the feeding and mating systems of the Galapagos land iguana caused by tourist disturbance (Edington and Edington 1986 as cited in Buckley 2001).

Tourism has for many years been focused on mountain and coastal areas. In the mountains, sources of damage include erosion and pollution from the construction of hiking

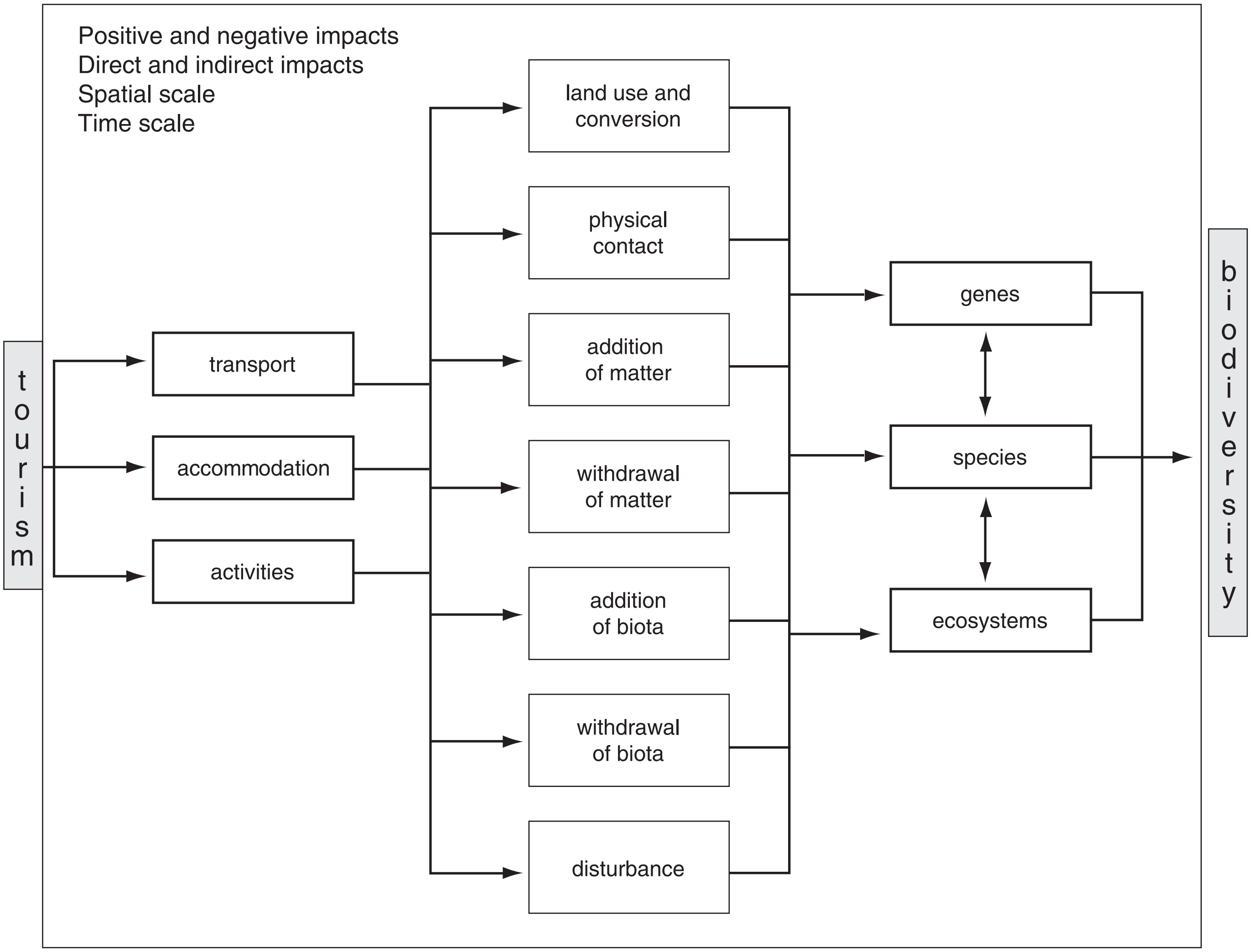


**Figure 7.12. Pathways of the Ecological Impacts of Tourism on Biodiversity** (van der Duim and Caalders 2002)

trails, bridges in high mountains, camp sites, chalets, and hotels (Frost 2001). In marine and coastal environments, impacts arise from inappropriate planning, irresponsible behavior by tourists and operators, and lack of education on and awareness of the impacts of, for example, tourist resorts along the coastal zones (Cater and Cater 2001; Halpenny 2001).

Tourism is a water-intensive activity with a large production of waste. The extraction of groundwater by some tourism activities can cause desiccation, resulting in loss of biological diversity. Moreover, the disposal of untreated effluents into surrounding rivers and seas can cause eutrophication, and it can also introduce pathogens into water bodies. Disposal of waste produced by the tourism industry may cause major environmental problems.

Negative socioeconomic and cultural consequences of tourism include impacts on local communities and cultural values (Wearing 2001). Increased tourism activities can cause an influx of people seeking employment or entrepreneurial opportunities who may not be able to find suitable employment. If an economy relies heavily on tourism, a recession elsewhere can result in a sudden loss of income and jobs. When tourism development occurs, economic benefits are sometimes unequally distributed among members of local communities. Lindberg (2001) points out that in some circumstances, tourism can actually increase inequalities, and thus relative poverty, in communities. However, there appears to be no evidence about whether this is a systematic problem or relatively infrequent. Negative cultural outcomes include intergenerational and gender conflicts, changes in traditional practices, and loss of access by indigenous and local communities to their land and resources as well as sacred sites. Positive outcomes include a renewed interest in maintaining local cultural practices.

Within the tourism industry and also within research on tourism, the notion of ''sustainable tourism'' has emerged to promote traveling with fewer negative impacts on sustainability. According to the World Tourism Organization, sustainable tourism development meets the needs of present tourists and host regions while protecting and enhancing opportunities for the future. It is envisaged as leading to management of all resources in such a way that economic, social, and aesthetic needs can be fulfilled while maintaining cultural integrity, essential ecological processes, biological diversity, and life support systems. Projects with headlines like ''ecotourism'' or ''alternative tourism'' have emerged under the overall premise of sustainable tourism. Though success stories do exist, there is evidence that the majority of projects cannot be genuinely conceived of as being sustainable (Collings 1999).

#### *7.2.2.8 Overview of Economic Drivers in the MA Scenarios*

The MA scenarios include a rich set of economic drivers, and Chapter 9 provides a more-detailed discussion of these. A useful summary statistic is the differences in per capita income. In the MA scenarios, per capita income grows two to four times between 2000 and 2050, depending on scenario. Total economic output grows three to six times during that period.

### 7.2.3 Sociopolitical Drivers

''Sociopolitical'' drivers encompass the forces influencing decision-making in the large conceptual space between economics and culture. The boundaries among economic, sociopolitical, and cultural driver categories are fluid, changing with time, level of analysis, and observer (Young 2002).

Sociopolitical driving forces have been seen as important in past environmental change (see, e.g., Redman 1999; de Vries and Goudsblom 2002). However, these drivers have been more the subject of taken-for-granted assumptions and speculation than sound theoretical and empirical research, so the basis for strong conclusions about how these drivers work is limited. This is an active area of research across many disciplines, so the state of knowledge is improving rapidly. In this regard it is important to remember the adage that the lack of evidence of an effect is not evidence for a lack of effect. Sociopolitical drivers may be some of the most fundamental influences on how humans influence the environment. They should always be given careful consideration in understanding environmental change, and they deserve high priority in future research agendas.

Some topics under the general theme of sociopolitical drivers have been well researched. For example, a strong literature examines governance of the commons at scales ranging from the local to the global.

Many writers have argued for the importance of democracy and equitable distribution of power for protecting the environment, and there are numerous accounts of how arbitrary uses of power harm the environment (see, for example, Ehrlich and Ehrlich 2004). When we turn to the scientific literature investigating the effects of democratic institutions and other political forms as drivers of environmental impact, however, systematic research is still in its early stages. There is some theoretical work of long standing (e.g., Beck 1992; Buttel 2003; Mol and Sonnenfeld 2000; Schnaiberg 1980; York and Rosa 2003). But once we move from the well-developed literature on institutions for commons governance, empirical and analytical research is still in the early stages of development. Thus we can characterize the directions current research is taking but cannot draw strong conclusions.

For convenience in discussing this general literature, we have divided sociopolitical drivers into four categories related to governance:

- the quantity of public participation in public decision-making,
- the makeup of participants in public decision-making,
- the mechanisms of dispute resolution, and
- the role of the state relative to the private sector.

#### *7.2.3.1 The Quantity of Public Participation in Public Decision-making*

The general role of the public in decision-making appears to be expanding, as evidenced by the extent of democratization. Despite some backsliding, there has been a trend away from centralized authoritarian governments and a rise of elected democracies. As well, there is some evidence of improving administrative competence across the developing world (Kaufmann et al. 2003). It is generally assumed that democratization leads to government actions that are friendlier to the environment, but the evidence in support of this assertion is limited (Congleton 1996; York et al. 2003a).

The literature on public participation in environmental assessment and decision-making is much more robust and indicates that such involvement at the local and regional level generally leads to more-sustainable approaches to managing resources (Stern and Fineberg 1996; Dietz and Stern 1998; Tuler and Webler 1999; Lubell 2000; Beierle and Cayford 2002; Dietz et al. 2003).

Finally, there is a substantial and robust literature on a key category of environmental problem—the governance of commons (Ostrom et al. 2002). Some strong generalizations have emerged from this literature that contrast with Hardin's original stark conclusions (Hardin 1968). We are more likely to govern commons sustainably when:

- ''Resources and use of the resources by humans can be monitored, and the information can be verified and understood at relatively low cost, . . .
- rates of change in resources, resource-user populations, technology and economic and social conditions are moderate,
- communities maintain frequent face-to-face communication and dense social networks—sometimes called social capital—that increase the potential for trust, allow people to express and see emotional reactions to distrust and lower the cost of monitoring behavior and inducing rule compliance,
- outsiders can be excluded at relatively low cost from using the resource . . . , and
- users support effect monitoring and rule enforcement'' (Dietz et al. 2003, p. 1908).

The challenge is to find ways of structuring decision-making processes that support the emergence of these conditions or that adapt when they do not obtain.

#### *7.2.3.2 The Makeup of Participants in Public Decision-making*

The voices heard in public decision-making and how they are expressed have changed, as evidenced in the changing role of women, the rise of civil society, and the growth of engaged fundamentalism. Democratic institutions have also encouraged decentralized decision-making, with the intended beneficiaries having a greater say in the decisions made. This trend has helped empower local communities, especially rural women and resource-poor households. Decentralization trends have also had an impact on decisions made by regional and international institutions, with the increasing involvement of NGOs and grassroots organizations, such as traditional peoples groups.

The power of NGOs arises in part from their ability to mobilize voters in societies where the average citizen does not participate actively in the political process. Hence, more openness and transparency in public decision-making enhances the influence of NGOs (Princen and Finger 1994).

#### 7.2.3.3 The Mechanisms of Dispute Resolution

The mechanisms by which nations solve their disputes, peaceful and otherwise, are changing. Although the cold war has ended, the persistence of regional and civil wars and other international conflicts in some parts of the world continues to be a matter of concern. There is an urgent need to understand the driving forces behind such conflicts and their impact on sustainable livelihoods and the natural resource base. (See Box 7.1.)

Numerous mechanisms have been proposed to help incorporate the views of diverse stakeholders into environmental decision-making (Renn et al. 1995). While it is not yet clear how these function in practice, there is a growing body of research on public participation in environmental assessment and decision-making, and several synthetic efforts to understand these processes are under way (U.S. National Research Council; Kasemir et al. 2003).

#### 7.2.3.4 The Role of the State Relative to the Private Sector

The declining importance of the state relative to the private sector—as a supplier of goods and services, as a source of employment, and as a source of innovation—seems likely to continue. The future functions of the state in provisioning public goods, security, and regulation are still evolving, particularly in the developing world. In all countries the implications of privatization trends on the sustainable management of the local and global resource base are still not clear. The old two-way relationships between governments and private firms have been radically changed with the emergence of large numbers of NGOs, which have become important actors in the political and social scene. For example, some environmental NGOs employ scientists who play important roles in bridging scientific communities to assess environmental problems, educating the public, and influencing the political process.

An important driver of the new role of NGOs has been improved communications technologies that make it easier for large numbers of like-minded people to work together. Clearly, there is a rapid transition under way in how we organize and communicate. A major intellectual effort to come to grips with this driver helps identify the issues but by no means provides a clear picture (Castells 1996).

#### 7.2.3.5 Education, Knowledge, and Sociopolitical Drivers

Democracy allows more participants into the political process, but what if some people know more than others, or if people know different things? Formal schooling increases economic productivity and the ability to comprehend and participate in the political process, but it is also likely to contribute to the loss of some indigenous and experiential knowledge. Formal education is often lowest among the poor who interact most directly with ecosystems.

Average levels of formal education are increasing around the globe, but with great differences in rates, especially within developing regions (United Nations 2003a). Some developing countries, such as China, have invested heavily in primary and secondary education over the past several decades and can anticipate an increasingly well educated population as educated children become educated adults. In contrast, other regions, such as South Asia and sub-Saharan Africa, have very low average education levels that will take decades to increase substantially (Lutz and Goujon 2001).

Formal education beyond secondary school becomes increasingly specialized. Knowledge narrowing, complemented by the economic gains of specialization provided by expanding markets, means the attention of any particular individual is increasingly focused on a small subset of the human enterprise. Thus knowledge and employment specialization, along with the shift to urban life, have separated people from traditional understandings of nature as a whole and divided modern understanding into multiple parts and disbursed it among people (Giddens 1990). Another consequence is that while the "volume" of knowledge is far greater today than at any time in the past, it is widely dispersed. The deep knowledge held by one type of experts is very difficult to link with that of other experts. And syntheses of knowledge into general information that can be widely conveyed to inform collective action are also difficult. The modern human dilemma can be characterized as the challenge of rallying disparate human knowledge of complex systems to inform action (Norgaard 2004).

Incorporating the knowledge of separate experts in democratic and bureaucratic systems presents its own challenges. The primary response, generally referred to as "progressive governance," has been to argue that the voice of experts should be heard before legislatures vote or administrators decide. Progressive governance is not without its own problems. The separate voices of different experts rarely speak coherently to systemic social and ecological problems, nor do they speak to the concerns of people, especially local people. Facts and values are not always separable, and experts end up speaking for particular interests even when they think they are speaking for the public. Experts also become captured by special interest groups, and government agencies can become an interest of their own. Interagency task forces, stricter peer review, and increasing public participation through hearings and other mechanisms offset some of these problems (Dupre 1986; Jasanoff 1990; Irwin 1995; Fischer 2000).

#### 7.2.3.6 Sociopolitical Drivers and Ecosystem Consequences

Widely accepted generalizations about the effects of sociopolitical drivers on ecosystems do not exist. Some examples

BOX 7.1

**War as a Driver of Change in Ecosystem Services and Human Well-being**

War acts as both a direct and an indirect driver of change in ecosystem services and human well-being, as nature becomes the intended victim or recipient of "collateral damage." The number of wars waged reached a maximum of 187 in the mid-1980s. That number was reduced by half by 2000 (Marshall et al. 2003). Most of these wars were internal conflicts. They were distributed highly unevenly across the world, predominantly in poor countries. (See MA *Current State and Trends,* Chapter 5, for a map of the distribution of internal wars from 1975 to 2003.)

During the twentieth century, 191 million people lost their lives in conflict-related incidents; 60% of these were non-military casualties (Krug 2002). Since World War II, more than 24 million people have been killed and another 50 million injured in state-sponsored wars and armed conflicts globally. Civilian casualties accounted for 90% of the dead. Between 1985 and 1995 alone, UNICEF estimated that wars have claimed the lives of 2 million children, wounded or disabled 4–6 million, orphaned 1 million, and left 12 million children homeless (UNICEF 1996; Pendersen 2002). Globally, armed conflicts around the world were responsible for the internal displacement of 11.7 million people during 1998 alone. In addition, armed conflicts forced 23 million people to seek refuge outside their countries in 1997 alone, while an additional 2.5 million abandoned their livelihoods and crossed national boundaries as a result of war-related violence (Krug 2002).

Environmental effects of warfare include damage to animals, defoliation, destruction of flora, degradation of soil, and loss of biodiversity (Pendersen 2002). The impacts of war on nature depend on the magnitude and duration of the conflict and its effects, the type of ecosystem involved (its resistance and resilience), the type of weapons used, the process of weapons production, and the cumulative effects sustained from the military campaigns. The main activities that result in protracted and persistent effects on ecosystem health, services, and human well-being are the manufacturing and testing of nuclear weapons, aerial and naval bombardment of landscapes, dispersal of landmines and de-mining, and the use and storage of military toxins and waste (Leaning 2000).

Ecological disturbance from armed conflict is not solely a contemporary issue. Scorched earth tactics (meant to inflict maximum damage to resources and facilities in an area in order to deny their use by the enemy) were used by the Greeks in the Peloponnesian wars (431–04 BC) (Thucydides 1989). Romans applied salts to soils in Carthage after their victory in the Punic wars (264–146 BC), and dykes were destroyed in the Netherlands to prevent a French invasion in 1792 (Bodansky 2003).

Modern warfare, however, has had particularly severe impacts. Chemical defoliants, bombs, and physical disruption by the United States army destroyed 14% of the Vietnamese total forest cover between 1961 and 1970, including 54% of the mangrove forests (Bodansky 2003).

In the first Gulf War in 1991, Iraq released about 2 million barrels of oil into the Persian Gulf and ignited 736 Kuwaiti oil wells, spreading clouds of black soot throughout the Middle East and the surrounding regions. The soot emission changed the local temperature, and the sulfur released with it contributed to acid rain. The effects suffered due to oil contamination included lesions and cancerous growths, sublethal effects of lower tolerance to environmental stress, and loss of insulation and motility by mammals from oiling of feathers and fur (World Conservation Monitoring Center 1991).

During the Eritrean war for independence from Ethiopia (1961–91), 30% forest cover of the country was reduced to less than 1%. The near-complete elimination of vegetation of some areas resulted in high rates of soil erosion with consequent problems of reduced crop yield, reduced wildlife populations, and sedimentation of rivers and reservoirs (Berhe in press).

Indirect impacts of wars include changes in land use as cultivators change crops, abandon fields, or retreat to more secure areas that are sometimes environmentally sensitive. Infrastructure damage or construction of new roads alters the incentives of an ecosystem's inhabitants (Westing 1988; W. Ghiorghis 1993; Berhe 2000). War-driven environmental degradation can initiate social degradation and protracted cycles of social and environmental decline by creating poverty, overexploitation of marginal resources, underdevelopment, and in extreme cases famine and social destruction (Lanz 1996; Berhe 2000, in press).

Since the fall of the Soviet Union, the danger of nuclear weapons has become a serious threat. It is estimated that a large-scale nuclear war could result in more than 1 billion deaths and injury of an equal number of people due to the combined effects of blast, fire, and radiation. Among the most serious environmental consequences of a nuclear war of this magnitude are subfreezing temperatures; a reduction in solar radiation at Earth's surface by half; triple the amount of UV-B radiation; increased doses of ionizing radiation from gamma and neuron flux of the fireball and radioactive debris fallout; chemical pollution of surface waters with pyrotoxins released from chemical storage areas; atmospheric pollution from the release of nitric oxide, ozone, and pyrogenic pollutants from the detonation; and release of toxic chemicals from secondary fires and storage areas (Ehrlich et al. 1983).

Landmines are not usually considered weapons of mass destruction, but more people have been killed and injured by anti-personnel mines than by nuclear and chemical weapons combined. Land mines maim or kill an estimated 400 people a week (International Campaign to Ban Landmines 2002). It is believed that there are about 80–110 million landmines spread in 82 countries, with another 230 million waiting to be deployed in 94 countries (Berhe 2000; International Campaign to Ban Landmines 2002). The distribution is not uniform. In Cambodia and Bosnia, there is approximately one mine in the ground for each citizen; in Afghanistan, Iraq, Croatia, Eritrea, and Sudan, the ratio is one mine for every two persons (Berhe 2000).

A landmine costs $3 to manufacture but $300–1,000 to clear (Nachón 2000). Landmines introduce nonbiodegradable and toxic waste of depleted uranium and 2,4,6-trinitrotoulene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazide (RDX, or Cyclonite), or tetryl as high-explosive filters. These compounds have been known to leach into soil and underground water as the metal or timber casing of the mine disintegrates (Gray 1997).

The impacts on ecosystem services and human well-being include access denial (which can lead to ecosystem recovery), disruption of land stability, pollution, and loss of biodiversity in the short run. These effects can be manifested as being biophysical, chemical, socioeconomic, or political in nature. The biophysical or chemical effects include destruction of soil structure: an increased rate of sediment transport by erosion and loads into streams; contamination with toxic pollutants; and a changing proportion, diversity, and productivity of flora and fauna coupled with habitat destruction. The socioeconomic or political effects include loss of income, food shortage, poverty, vulnerability, change in population per unit area, increased social polarization, declining health care, migration or displacement, destruction of essential infrastructures, arrested development of regions, and sociopolitical instability (Berhe 2000).

can be found in the final section of this chapter, on interactions among drivers and ecosystems.

#### *7.2.3.7 Overview of Sociopolitical Drivers in the MA Scenarios*

Sociopolitical drivers enter the MA scenarios in a number of ways—human capital and research investments, extent of international cooperation and attitudes toward environmental policies, and lifestyle choices affecting energy demand. (See Chapter 9 for further information on the different assumptions made about these in the four MA scenarios.)

### 7.2.4 Cultural and Religious Drivers

The word "culture" has many definitions in both the social sciences and in ordinary language. To understand culture as a driver of ecosystem change, it may be most useful to focus on the values, beliefs, and norms that a group of people share and that have the most influence on decision-making about the environment. (Of course, other aspects of culture, such as risk perception and willingness to accept risk, or preference for present versus future benefits, also influence environmental decision-making, but they are less salient to this discussion.) In this sense, culture conditions individuals' perceptions of the world, influences what they consider important, and suggests courses of action that are appropriate and inappropriate. And while culture is most often thought of as a characteristic of national or ethnic groups, this definition also acknowledges the emergence of cultures within professions and organizations, along with the possibility that an individual may be able to draw on or reconcile more than one culture.

There is a substantial literature examining the role of culture in shaping human environmental behavior. Productive work on this has focused on approaches that link directly with the social psychology of environmental concern and the influence of values, beliefs, and norms on individual decisions. Broad comparisons of whole cultures have not proved useful because they ignore vast variations in values, beliefs, and norms within cultures. But a growing number of studies are conducted in parallel in multiple societies and allow for systematic examination of the role of culture without overgeneralizing (Dunlap and Mertig 1995; Rosa et al. 2000; Hanada 2003). This work builds on social psychological analyses conducted within nations and cultures and then systematically compares them across nations.

Consumption behavior, especially in affluent nations and within affluent groups in developing nations, may be a particularly important driver of environmental change, but its cultural elements have not been extensively studied (Stern et al. 1997). It is clear that there is broad concern with the environment throughout the globe (Dunlap et al. 1993), but it is less clear how that concern translates into either changes in consumer behavior or political action. This is because consumption has many determinants beyond satisfying basic human needs. Values and beliefs regarding the environmental impacts of consumption may play a role, but consumption is also driven by peer group expectations and efforts to establish a personal identity, both of which are the targets of advertising. Further, some consumption is relatively easy to change (such as turning off a light), while other aspects require substantial investments (such as buying a high-efficiency refrigerator) (Dietz and Stern 2002).

A substantial body of literature provides lessons on how policies and programs can most effectively produce cultural change around environmental behavior (Dietz and Stern 2002). Obviously, the relationship between culture and behavior is context-specific. Indeed, one important lesson of research on this topic is that overarching generalizations are seldom correct.

The ability of culture to shape behavior depends on the constraints faced by individuals, and the effects of changing constraints on behavior depend on the culture of the individuals encountering the changes (Gardner and Stern 1995; Guagnano et al. 1995). In many circumstances changing values, beliefs, and norms will have no effect on behavior because individuals face structural constraints to pro-environmental behavior. (For example, public education about the problems of using tropical hardwoods will have little impact if people have no way of knowing the origins of lumber they may purchase.) In other circumstances changing constraints on behavior will have little effect because the mix of values, beliefs, and norms provides little reason to behave in an environmentally protective way. (For instance, making environmentally friendly food choices available may not influence consumptions if people are not aware of the environmental impacts of their consumption patterns).

Just as it is important to differentiate structural constraints (how hard it is to behave in an environmentally protective way) from culture (values, norms, and beliefs), it is also important to realize that there are multiple forms of pro-environmental behavior, and different factors may drive them. For example, Stern (Stern et al. 1999; Stern 2000) notes that environmental consumer behavior, environmental political behavior, and a willingness to make sacrifices to protect the environment, while positively correlated, are somewhat distinct and are influenced by different elements of culture.

There has been extensive and diverse research on the influence of values on pro-environmental behavior. A tradition stretching from Kluckholm (1952) through Rokeach (1968, 1973) to Schwartz (1987, 1990, 1992) has provided theoretical and empirical arguments to support the idea that values—things that people consider important in their life—are important in shaping behavior and are relatively stable over the life course (Schwartz 1996). Two strains of research have applied this logic to environmental concerns. Inglehart (1995) has suggested that a set of values he labels "post-materialist" predict environmental concern. His argument is that only once people have achieved a reasonable degree of material security can they assign priority to issues such as the environment. This argument has some strong parallels to the Environmental Kuznets Curve and to the ecological modernization theory in sociology (York et al. 2003b). However, as indicated, there is considerable controversy regarding the empirical support for this argument at either the individual or the national level (e.g., Brechin and Kempton 1994; Dunlap and Mertig 1995; Brechin and Kempton 1997; Dunlap and Mertig 1997; Brechin 1999; Stern et al. 1999; York et al. 2003b).

A number of researchers have suggested that altruism is a key value underpinning environmental concern, and that the scope of altruism may be limited to other humans or may extend to other species and the biosphere itself (Dunlap et al. 1983; Merchant 1992; Stern et al. 1993; Karp 1996). Empirical work in this tradition has deployed Schwartz's cross-cultural measures of values, and finds fairly consistent support for the idea that altruism predicts environmental concern, as well as evidence that traditional values—which might be termed conservatism and appear to be related to fundamentalism in many faiths (Schwartz and Huismans 1995)—lead to less concern with the environment (e.g., Kempton et al. 1995; Karp 1996; Schultz and Zelezny 1998; Schultz and Zelezny 1999; Stern et al. 1999).

The social psychological literature places considerable emphasis on beliefs as predictors of behaviors. At one level, this literature emphasizes very specific beliefs about a behavior—its consequences, the difficulty in conducting it, and so on (Ajzen and Fishbein 1980; Ajzen 1991). While this approach is helpful in designing interventions to change environmentally significant behavior, such beliefs are generally not what is thought of as culture. However, it has been argued that broad general beliefs about the environment and human interactions with it provide a backdrop that influence the acceptability of or resistance to more specific beliefs (Stern et al. 1995).

One of the most widely used measures of environmental concern, the ''new ecological paradigm,'' can be interpreted as a measure of such general beliefs (Dunlap et al. 2002). The idea is that people vary in the degree to which they think that human interventions can cause significant harm to the environment. Variation in this general view makes individuals more or less accepting of new information about specific environmental problems. There is evidence that this new paradigm as well as values influence risk perception (Whitfield et al. 1999), including perception of ecological risk (Slimak 2003).

Norms are also a key part of culture related to environmental behavior. Norms signal to the individual what is appropriate behavior. Substantial work has been done on what activates norms regarding pro-environmental behavior (Van Liere and Dunlap 1978; Stern et al. 1986). Norms have been shown to be particularly important in local commons management, where they often guide behaviors that prevent overexploitation of a common pool resource (Ostrom et al. 2002).

Flowing from White's essay (White 1967), there has been substantial interest in the possible influences of religion on environmental concern and pro-environmental behavior. Some work on values has shown that traditional values are negatively related to environmental concern. There is a substantial literature in the United States that seems to indicate that adherents to fundamentalist Christian beliefs have less environmental concern than those with more liberal or moderate beliefs (Eckberg and Blocker 1989, 1996; Kanagy and Willits 1993).

While the social psychological literature is quite rich, as noted, the literature on cross-national comparisons is just emerging. The implications of that literature for our understanding of how environmental policy might be developed are unclear. And work on how environmentally relevant values, beliefs, and norms change is still in its earliest stages (but see Richerson et al. 2002).

#### *7.2.4.1 Cultural and Religious Drivers and Ecosystem Consequences*

It is common to hear arguments that we can best protect ecosystems, and by implication the services they provide, by changing values, beliefs, and norms. Yet as this section has described, values, beliefs, and norms—culture—are complex in themselves and their links to environmentally consequential behavior add further complexity. Changing values or beliefs will have little effect if changes in behavior to benefit the environment have high costs in time or money. In other cases, simply making people aware of the ecosystem consequences of their behavior can bring about substantial change, such as the growing demand for ''ecosystem-friendly'' consumer goods (Thogersen 2002). While cultural and religious factors may have a substantial influence on ecosystems, research has shown that broad generalizations are unwarranted and that analyses must always be context-specific.

#### *7.2.4.2 Overview of Cultural and Religious Drivers in the MA Scenarios*

Few cultural and religious drivers are built explicitly into the MA scenario quantitative modeling. However, changes in culture are an important part of the qualitative elements of some of the scenarios, particularly in Adapting Mosaic and to a certain extent in TechnoGarden. Both scenarios are built on the assumption that a general shift will occur in the way ecosystems and their services are valued. In both cases decision-makers at various scales develop a proactive approach to ecosystem management, but they pursue different management strategies to reach this goal. In TechnoGarden, the supply of ecosystem services is maintained by controlling ecosystem functions via technology. In Adapting Mosaic, the aim is to create a set of flexible, adaptive management options through a learning approach. Culturally diverse forms of learning about and adapting to ecosystem changes are fostered. Devising ways of incorporating traditional ecological and local knowledge into management processes and protecting the cultural and spiritual values assigned to nature in various cultures become part of the developed strategies.

### 7.2.5 Science and Technology Drivers

The development and diffusion of scientific knowledge and technologies that exploit knowledge have profound implications for ecological systems and human well-being. The twentieth century saw tremendous advances in understanding how the world works physically, chemically, biologically, and socially and in the applications of that knowledge to human endeavors. Earlier sections have documented examples of tremendous productivity gains in many industries.

From the introduction of the automobile in the early years to commercialization of genetically modified crops and widespread use of information technology more recently, many new products drew both praise and damnation regarding their effects on ecosystems. The twenty-first century is likely to see continued breathtaking advances in applications of materials science, molecular biology, and information technology—with real potential to improve human well-being and uncertain consequences for ecosystems.

Humans have been extremely successful in institutionalizing the process of scientific and technical change. Organizational structures that encourage researchers to make breakthroughs and to use them to develop potentially valuable products—such as research universities, publicly funded research centers, public-private collaborations for research and development, private research programs, regulatory institutions, and international agreements that collectively determine intellectual property rules (patents and copyrights, for instance)—are either in place or being implemented in the industrial world. However, they are not in place in most developing countries. Furthermore, institutions to use and reward development of indigenous knowledge are not well developed.

Society's ability to manage the process of product dissemination—identifying the potential for adverse consequences and finding ways to minimize them—has not always kept pace with our ability to develop new products and services. This disparity became especially obvious as the introduction of genetically modified crops met widespread opposition in some parts of the world. The protests in part resulted from the speed of advancement, as the rate of commercial adoptions of the first products of this new technology was unprecedented. At least 30 years passed between the development and widespread use of hybrid maize in industrial countries. For semi-dwarf rice and wheat in developing countries, a similar rate of use was reached only 15 years after development began. But use of genetically modified soybeans reached similar levels of use after only 5 years in Argentina and the United States. The use of the Internet accelerated worldwide communication and the organization of protests.

The state of scientific and technical knowledge at any moment depends on the accumulation of knowledge over time. Decision-makers can affect the rate of change in scientific and technical knowledge through setting research priorities and changing levels of funding. Domestic government funding for science and technology is driven by objectives such as scientific education, technology development, export markets, commercialization and privatization, and military power. The private sector responds to the perceived future for their products, looking for those that will be the most acceptable and profitable.

#### 7.2.5.1 Innovation and Technological Change

The importance of "advances in knowledge" and technology in explaining the historical record of productivity growth has already been mentioned. In the original study on contributions of productivity growth to overall growth by Solow (1957), productivity enhancements were estimated to account for 87% of per capita growth (the remainder was attributed to increases in capital inputs). Since then, further methodological and statistical refinements have reduced the unexplained "residual" of productivity growth that is equated to advances in knowledge and technology, but they remain the largest single source of long-run productivity and economic growth. Science and technology are estimated to have accounted for more than one third of total GDP growth in the United States from 1929 to the early 1980s (Denison 1985), and for 16–47% of GDP growth in selected OECD countries for the period 1960 to 1995 (Table 10.1 in Barro and Sala-i-Martin 2004).[4]

The observed slowdown in productivity growth rates from the early 1970s to the mid- 1990s is generally interpreted as a weakening of the technological frontier in the OECD countries (Maddison 1995; Barro 1997), although quantitative statistics (and even everyday experience) do not corroborate the perception of a slowdown in technological innovation and change. An alternate interpretation is that the OECD countries have moved out of a long period of industrialization and into post-industrial development as service economies. In such economies, productivity is hard to measure, partly because services include a mixture of government, nonmarket, and market activities, partly because economic accounts measure services primarily via inputs (such as the cost of labor) rather than outputs, and partly because it is difficult to define service quality. Nevertheless, labor productivity in the service sector appears to grow more slowly than in the agricultural and industrial sectors (Millward 1990; Baumol 1993).

Finally, another interpretation is that productivity growth lags behind technological change because institutional and social adjustment processes take time to be implemented (Freeman and Perez 1988; David 1990). Once an appropriate "match" (Freeman and Perez 1988) between institutional and technological change is achieved, productivity growth accelerates. Maddison (1995) observed that the nineteenth century productivity surge in the United States was preceded by a long period of investment in infrastructure. Landes (1969) notes that both the German and Japanese economic accelerations were preceded by long periods of investment in education. Maddison (1995) has further suggested that recent developments in information technology involve considerable investment, both in hardware and in human learning. There is some preliminary evidence that the payoff from this investment is beginning to be important in the early twenty-first century.

#### 7.2.5.2 Agricultural Science and Technology

We focus here on agricultural science and technology because of its obvious implications for land conversion and widespread consequences for many ecosystems. The ground-breaking research of Gregor Mendel in the 1860s on the heritability of phenotypical characteristics in garden peas laid the foundation for plant and livestock breeding research and the improvement of food crops in the twentieth century (Huffman and Evenson 1993). Since the beginning of that century, there have been three waves of agricultural biological technology development and diffusion.

The first wave took place mainly in North America and Europe in the 1930s and focused on important temperate climate crops. The discovery of hybridization—in which a cross of two genetically very different parent plants can produce a plant of greater vigor and higher yield than the parents—set the stage for major yield improvements in some of the most important food crops, especially maize. The first maize hybrids were commercially available for farmers in the U.S. Corn Belt in the 1930s. Average U.S. maize yields improved from 24.4 bushels per acre (1.53 tons per hectare) in 1860 to 116.2 bushels per acre (7.31 tons per hectare) in 1989, a more than fourfold increase over about 130 years. But even crops such as wheat, for which hybridization has not been commercially viable, saw similar improvements. Wheat yields grew from 11.0 bushels per acre (0.74 tons per hectare) in 1860 to 32.8 bushels per acre (2.21 tons per hectare) in 1989 (Huffman and Evenson 1993).

Some of the key developments were agricultural research systems that included universities, agricultural field stations, agricultural input companies, and extension services covering the chain from basic crop improvement research via field trials to disseminating information and new seed material to farmers (Ruttan 2001).

Agronomic research on improved inputs for crop production like fertilizer or pesticides and new agricultural management practices emerged, which further enhanced crop yields in farmers' fields. Funding for organized agricultural research was mainly provided by the public sector in the first half of the century, while the importance of private-sector research grew substantially in the second half as the private sector gained legal rights to protect genetic modifications (Huffman and Evenson 1993). In labor-scarce countries, particularly the United States, the private sector played a central role from the beginning in the development of agricultural machinery.

The second wave of agricultural technology development was particularly important in the developing world because it extended plant breeding and nutrient management techniques to important food crops in low-income countries. Since the early 1960s, productivity growth has been significant for rice in Asia, wheat in irrigated and favorable production environments worldwide, and maize in Mesoamerica and selected parts of Africa and Asia. High rates of investment in crop research, infrastructure, and market development combined with appropriate policy support fueled this land productivity (Pingali and Heisey 2001).

The Green Revolution strategy for food crop productivity growth was explicitly based on the premise that, given appropriate institutional mechanisms, technology spillovers across political and agro-climatic boundaries can be captured. Hence the Consultative Group on International Agricultural Research was established specifically to generate spillovers, particularly for nations that are unable to capture all the benefits of their research investments.

The major breakthroughs in yield potential that epitomize the Green Revolution came from conventional plant breeding approaches, characterized as crossing plants with different genetic backgrounds and selecting from among the progeny individual plants with desirable characteristics. Repeating the process over several generations leads to plant varieties with improved characteristics such as higher yields, improved disease resistance, and improved nutritional quality. The yields for the major cereals, especially with increased use of inorganic fertilizers with high nitrogen content, have continued to rise at a steady rate after the initial dramatic shifts in the 1960s for rice and wheat. For example, Table 7.5 shows that yields in irrigated spring wheat rose at the rate of 1% per year over the past three decades, an increase of around 100 kilograms per hectare per year (Pingali and Rajaram 1999).

In addition to work on shifting the yield frontier of cereal crops, plant breeders continue to have successes in the less glamorous areas of maintenance research. These include development of plants with durable resistance to a wide spectrum of insects and diseases, plants that are better able to tolerate a variety of physical stresses, crops that require significantly fewer days from planting to harvest, and cereal grain with enhanced taste and nutritional qualities.

The third, ongoing wave of agricultural technology development has been called the Gene Revolution and is based on techniques of transferring genetic material from one organism to another that would not occur via normal reproductive methods. The early phase of this wave was characterized by the development of a few commercial products (glyphosate-resistant soybeans, and maize and cotton that are resistant to lepidopteran pests), principally by private research firms (Nelson 2001). These early products of genetic engineering do not have higher potential yields than traditional varieties, but they often have higher effective yields because they reduce the cost of pest control. Varieties of food crops with other desirable characteristics such as increased beta-carotene content (the so-called golden

**Table 7.5 Rate of Growth of Wheat Yield by Mega-environment, Elite Spring Wheat Yield Trial, 1964–95.** Wheat breeders classify the developing world's spring wheat-growing areas into six distinct mega-environments: irrigated (ME1); high rainfall (ME2); acid soil (ME3); drought-prone (ME4); high temperature (ME5); and high latitude (ME6). A mega-environment is a broad, frequently transcontinental but not necessarily contiguous area occurring in more than one country, with similar biotic and abiotic stresses, cropping system requirements, volume of production, and, possibly, consumer preferences (Pingali and Rajaram 1999; Lantican et al. 2003).

| Period | ME1–Irrigated | ME2–High Rainfall | ME4–Drought-prone | ME5–High Temperature |
|---|---|---|---|---|
| | *(percent per year/kilograms per year)* | | | |
| 1964–78 | 1.22 | 1.72 | 1.54 | 1.41 |
| | 71.6 | 81.5 | 32.4 | 34.9 |
| 1979–99 | 0.82 | 1.16 | 3.48 | 2.10 |
| | 53.5 | 62.5 | 87.7 | 46.1 |

rice), increased drought tolerance (wheat), and virus resistance (papaya) are in various stages of development.

Substantial empirical evidence exists on the production, productivity, income, and human welfare impacts of modern agricultural science and the international flow of modern varieties of food crops. Evenson and Gollin (2003) provide detailed information for all the major food crops on the extent of adoption and impact of improved variety use. The adoption of modern varieties during the first 20 years of the Green Revolution—aggregated across all crops—reached 9% in 1970 and rose to 29% in 1980. In the subsequent 20 years, far more adoption has occurred than in the first two decades. By 1990, adoption of improved varieties had reached 46%, and it was 63% by 1998. Moreover, in many areas and in many crops, first-generation modern varieties have been replaced by second and third generations of improved varieties (Evenson and Gollin 2003).

Much of the increase in agricultural output over the past 40 years has come from an increase in yields per hectare rather than an expansion of area under cultivation. For instance, FAO data indicate that for all developing countries, wheat yields rose by 208% from 1960 to 2000, rice yields rose 109%, maize yields rose 157%, potato yields rose 78%, and cassava yields rose 36% (FAOSTAT). (See MA *Current State and Trends,* Chapter 26, for information on crop area expansion.) Trends in total factor productivity are consistent with partial productivity measures, such as rate of yield growth. Pingali and Heisey (2001) provide a comprehensive compilation of total factor productivity evidence for several countries and crops.

Widespread adoption of improved seed-fertilizer technology led to a significant growth in food supply, contributing to a fall in real food prices. The primary effect of agricultural technology on the non-farm poor, as well as on the rural poor who are net purchasers of food, is through lower food prices.

The effect of agricultural research on improving the purchasing power of the poor—both by raising their incomes and by lowering the prices of staple food products—is probably the major source of nutritional gains associated with agricultural research. Only the poor go hungry. Because a relatively high proportion of any income gains made by the poor is spent on food, the income effects of research-induced supply shifts can have major nutritional implications, particularly if those shifts result from technologies aimed at the poorest producers (Pinstrup-Andersen et al. 1976; Hayami and Herdt 1977; Scobie and Posada 1978; Binswanger 1980; Alston et al. 1995).

Several studies have provided empirical support to the proposition that growth in the agricultural sector has economy-wide effects. One of the earliest studies showing the linkages between the agricultural and nonagricultural sectors was done at the village level by Hayami et al. (1978). Hayami provided an excellent micro-level illustration of the impacts of rapid growth in rice production on land and labor markets and the nonagricultural sector.

More recent assessments on the impacts of productivity growth on land and labor markets have been done by Pinstrup-Andersen and Hazell (1985) and by David and Otsuka (1994). Pinstrup-Andersen and Hazell (1985) argued that landless labor did not adequately share in the benefits of the Green Revolution because of depressed wage rates attributable to migrants from other regions. David and Otsuka (1994), on the other hand, found that migrants shared in the benefits of the Green Revolution through increased employment opportunities and wage income. The latter study also documented that rising productivity caused land prices to rise in the high-potential environments where the Green Revolution took off. For sector-level validation of the proposition that agriculture does indeed act as an engine of overall economic growth, see Hazell and Haggblade (1993), Delgado et al. (1998), and Fan et al. (1998).

The profitability of farming systems using improved varieties has been maintained despite falling food prices (in real terms), owing to a steady decline in the cost per ton of production (Pingali and Traxler 2002). Savings in production costs have come about from technical change in crop management and increased input-use efficiencies. Once improved varieties have been adopted, the next set of technologies that makes a significant difference in reducing production costs includes machinery, land management practices (often in association with herbicide use), fertilizer use, integrated pest management, and (most recently) improved water management practices.

Although many Green Revolution technologies were developed and extended in package form (such as new plant varieties plus recommended fertilizer, pesticide, and herbicide rates, along with water control measures), many components of these technologies were taken up in a piecemeal, often stepwise manner (Byerlee and Hesse de Polanco 1986). The sequence of adoption is determined by factor scarcities and the potential cost savings achieved. Herdt (1987) provided a detailed assessment of the sequential adoption of crop management technologies for rice in the Philippines. Traxler and Byerlee (1992) provided similar evidence on the sequential adoption of crop management technologies for wheat in Sonora, northwestern Mexico.

Although high-potential environments gained the most in terms of productivity growth from the Green Revolution varieties, the less favorable environments benefited as well through technology spillovers and through labor migration to more productive environments. According to David and Otsuka (1994), wage equalization across favorable and unfavorable environments was one of the primary means of redistributing the gains of technological change. (Wages of workers in unfavorable environments are pulled up by demand for additional labor in the favorable environments.) Renkow (1993) found similar results for wheat grown in high- and low-potential environments in Pakistan.

Byerlee and Moya (1993), in their global assessment of the adoption of improved wheat varieties, found that over time the adoption of modern varieties in unfavorable environments caught up to levels of adoption in more favorable environments, particularly when germplasm developed for high-potential environments was further adapted to the more marginal environments. In the case of wheat, the rate of growth in yield potential in drought-prone environments was around 2.5% per year during the 1980s and 1990s (Lantican et al. 2003). Initially the growth in yield potential for the marginal environments came from technological spillovers as varieties bred for the high-potential environments were adapted to the marginal environments. During the 1990s, however, further gains in yield potential came from breeding efforts targeted specifically at the marginal environments.

Since the 1990s, the locus of agricultural research and development has shifted dramatically from the public to the private multinational sector. Three interrelated forces in this latter wave of globalization are transforming the system for supplying improved agricultural technologies to the world's farmers. The first is the evolving environment for protecting intellectual property in plant innovations. The second is the rapid pace of discovery and the growth in importance of molecular biology and genetic engineering. Finally, agricultural input and output trade is becoming more open in nearly all countries. These developments have created a powerful new set of incentives for private research investment, altering the structure of the public/private agricultural research endeavor, particularly with respect to crop improvement (Falcon and Fowler 2002; Pingali and Traxler 2002).

#### *7.2.5.3 Science and Technology Drivers and Ecosystem Consequences*

The consequences of technical change for ecosystems are as diverse as those for economic drivers, because technical change alters the interplay among inputs, resource use, and outputs. Two examples—in agriculture and fisheries—illustrate this complexity. The development of high-yielding crop varieties meant that less land could be used to produce the same amount of food with positive effects on the condition of the unconverted ecosystems. The invention of the Haber-Bosch process to convert atmospheric nitrogen cheaply into nitrogenous fertilizer meant that plants with high yield response to this fertilizer were favored in the marketplace. More nitrogen was applied to fields, altering dramatically the natural nitrogen cycle, with negative consequences in coastal ecosystems. (See later discussion on nitrogen use and ecosystem consequences.) Use of pesticides also had unintended consequences, such as the reduction in availability of by-product protein from irrigated fields (fish and amphibians).

Improved marine fishing technologies have made it possible to extract considerable fish biomass from the marine system. In fact, humankind has probably reached the maximum (and in some places exceeded) levels of fish biomass removal before significant ecosystem changes are induced. (Since fish biomass is a small fraction of the marine standing biomass, current fish extraction probably removes only a small portion of total marine biomass; recent initiatives such as the Scientific Committee on Ocean Research workshop on the impacts of fishing on marine ecosystems are trying to address the question of impacts.) For example, in the Gulf of Thailand higher trophic animals are no longer present and the system is dominated by lower trophic species with a high biomass turnover (Christianson 1998). Research in West Africa (Alder and Sumaila 2004) and the North Atlantic (Christianson et al. 2003) indicates similar changes.

A less diverse system is in principle more vulnerable (less resistant) to perturbations such as disease and climate change, but there is little documented evidence that the loss of fish biomass is driving changes in the carbon and nitrogen cycle as well as diseases. In parts of the Caribbean, removal of the top predators ultimately resulted in the areas shifting from coral-dominated reefs to algal-dominated ones. In this case, the removal of top predators resulted in reefs dominated by sea urchins, but a disease wiped them out so there were few animals left to clean algae from the corals, resulting in a rapid shift from coral to algal-dominated reefs. (This process is described in detail in Chapter 19 of the *Current State and Trends* volume.)

#### *7.2.5.4 Overview of Science and Technology Drivers in the MA Scenarios*

The MA scenarios include a number of different science and technology drivers. A qualitative assessment about changes in aggregate technology development is implemented in a variety of assumptions about crop yield changes, energy and water efficiency, and materials intensity. The assumptions about the development of science and technology in each of the scenarios can be found in Chapter 9.

## 7.3 Direct Drivers

This section reviews some of the most important direct drivers of ecosystem condition: climate variability and change, plant nutrient use, land conversion, invasive species, and diseases.

### 7.3.1 Climate Variability and Change

Key climatic parameters that affect ecological systems include mean temperature and precipitation and their variability and extremes, and in the case of marine systems, sea level. In this section we review the available record on climate and the drivers of climate variability and change.

This section is primarily based on the expert and government peer-reviewed reports from the Intergovernmental Panel on Climate Change—especially on the Working Group I Report of the Third Assessment Report (Houghton et al. 2001; IPCC 2002) and the Special Report on Emissions Scenarios (Nakićenović et al. 2000)—and on the Convention on Biological Diversity Technical Series No. 10 (Secretariat of the Convention on Biological Diversity 2003). This section highlights the key conclusions of these assessments, which, given their comprehensive nature and recent publication, are still valid.

#### *7.3.1.1 Observed Changes in Climate*

The global-average surface air temperature has increased by 0.6 ± 0.2° Celsius since about 1860. (See Figure 7.13 in Appendix A.) The record shows a great deal of spatial and temporal variability; for example, most of the warming occurred during two periods (1910–45 and since 1976). It is very likely that the 1990s was the warmest decade, and 1998 the warmest year, of the instrumental record. Extending the instrumental record with proxy data for the Northern Hemisphere indicates that over the past 1,000 years, the twentieth century's increase in temperature is likely to have been the largest of any century, and the 1990s was likely the warmest decade (IPCC 2002, p. 42). On average, nighttime daily minimum temperatures over land have increased at about twice the rate of daytime daily maximum temperatures since about 1950 (approximately 0.2° versus 0.1° Celsius per decade). This has lengthened the freeze-free season in many mid- and high-latitude regions.

Precipitation increased by 0.5–1% per decade in the twentieth century over most mid- and high-latitudes of the Northern Hemisphere continents. Rainfall has decreased over much of the sub-tropical land areas (−0.3% per decade), although it appeared to recover in the 1990s. It is likely that there has been an increase in heavy and extreme precipitation events, on average, in the mid- and high-latitudes of the Northern Hemisphere.

There has been a widespread retreat of mountain glaciers in nonpolar regions during the twentieth century, decreases of about 10% in the extent of snow cover since the late 1960s, and a reduction of about two weeks in the annual duration of lake- and river-ice cover in the mid- and high latitudes of the Northern Hemisphere over the twentieth century. Northern Hemisphere spring and summer sea-ice extent has decreased by about 10–15% since the 1950s. It is likely that there has been about a 40% decline in Arctic sea-ice thickness during late summer to early autumn in recent decades and a considerably slower decline in winter sea-ice thickness.

Global-average sea level rose 10–20 centimeters during the twentieth century. Warm episodes of the El Niño/Southern Oscillation phenomenon have been more frequent, persistent, and intense since the mid-1970s. This recent behavior has been reflected in regional variations of precipitation and temperature over much of the tropics and sub-tropics.

#### *7.3.1.2 Observed Changes in Atmospheric Composition: Greenhouse Gases and Aerosol Precursors*

Since 1750, the atmospheric concentration of carbon dioxide has increased by about 32% (from about 280 to 376 parts per million in 2003. Approximately 60% of that increase (60 ppm) has taken place since 1959 (Keeling and Whorf, at cdiac.esd.ornl.gov/trends/co2/sio-mlo.htm). (See Figure 7.14 in Appendix A.) Nearly 80% of the increase during the past 20 years is due to fossil fuel burning, with the rest being due to land use changes, especially deforestation and, to a lesser extent, cement production. The rate of increase of atmospheric $CO_2$ concentration has been about 0.4% per year over the past two decades. During the 1990s, the annual increase varied by a factor of three, with a large part of this variability being due to the effect of climate variability on $CO_2$ uptake and release by land and oceans.

Atmospheric methane concentrations have increased by a factor of 2.5 since 1750 (from about 700 to 1,750 parts per billion), and they continue to increase. The annual increase in $CH_4$ atmospheric concentrations became slower and more variable in the 1990s compared with the 1980s. The atmospheric concentration of nitrous oxide has increased by about 17% since 1750 (from about 270 to 315 parts per billion).

The atmospheric concentrations of many of the halocarbon gases that are both ozone-depleting and greenhouse gases are either decreasing or increasing more slowly in response to reduced emissions under the regulations of the Montreal Protocol on the ozone layer and its amendments. Their substitute compounds and some other synthetic compounds (such as perfluorocarbons and sulfur hexafluoride) are increasing rapidly in the atmosphere, but from recent near-zero concentrations.

Tropospheric ozone has increased by about 35% since 1750 due to anthropogenic emissions of several ozone-forming gases (non-methane hydrocarbons, $NO_x$, and carbon monoxide). Ozone varies considerably by region, and because of its short atmospheric lifetime it responds much more quickly to changes in precursor emissions than the long-lived greenhouse gases, such as $CO_2$.

#### *7.3.1.3 Projections of Changes in Atmospheric Composition: Greenhouse Gases and Aerosol Precursors*

Carbon emissions due to fossil-fuel burning are virtually certain to be the dominant influence on the trends in atmospheric $CO_2$ concentration during the twenty-first century. As the $CO_2$ concentration increases and climate changes, the oceans and land will take up a progressively decreasing proportion of anthropogenic carbon emissions. By the end of the twenty-first century, models project atmospheric concentrations of $CO_2$ of 540–970 parts per million. (See Figure 7.15 in Appendix A.) This range of projected concentrations is primarily due to differences among the emissions scenarios (the IPCC-SRES scenarios show a range of 5–28 gigatons of carbon per year in 2100, compared with 7.1 gigatons in 1990); different carbon model assumptions would add at least ±10% uncertainty to these projections. Sequestration of carbon by changing land use could influence atmospheric $CO_2$ concentration. However, even if all of the carbon so far released by land use changes could be restored to the terrestrial biosphere (through reforestation, for example), projected levels of $CO_2$ concentration would be reduced by only 40–70 parts per million.

Model projections of the emissions of the non-$CO_2$ greenhouse gases vary considerably by 2100 across the IPCC-SRES emissions scenarios. Annual anthropogenic $CH_4$ and $N_2O$ emissions are projected to be 270–890 teragram $CH_4$ and 5–17 teragram N in 2100, compared with 310 teragram $CH_4$ and 6.7 teragram N in 1990. By the end of the century, models project the atmospheric concentrations of $CH_4$ to be 1,550–3,750 parts per billion and of $N_2O$ to be 340–460 parts per billion.

Model projections of the emissions of the precursors of tropospheric ozone—that is, CO, NMHCs, and $NO_x$—also vary considerably by 2100 across the IPCC-SRES emissions scenarios. Annual anthropogenic emissions are projected to be 360–2,600 teragram CO, 90–420 teragram NMHCs, and 19–110 teragram N in 2100, compared with about 880 teragram CO, 140 teragram NMHCs, and 31 teragram N in 1990. In some scenarios, tropospheric ozone would become as important a radiative forcing agent as $CH_4$ and would threaten the attainment of air quality targets over much of the Northern Hemisphere.

The IPCC-SRES scenarios primarily project decreases in anthropogenic sulfur dioxide emissions, leading to projected decreases in the atmospheric concentrations of sulfate aerosols. Model projections of the emissions of $SO_2$ vary considerably by 2100 across the IPCC-SRES emissions scenarios. Annual anthropogenic $SO_2$ emissions are projected to be 20–60 teragram S in 2100, compared with about 71 teragram S in 1990. In addition, natural aerosols (such as sea salt, dust, and emissions leading to the production of sulfate and carbon aerosols) may increase as a result of changes in climate and atmospheric chemistry.

#### *7.3.1.4 Existing Projections of Changes in Climate*

The global climate of the twenty-first century will depend on natural changes and the response of the climate system to human activities. Climate models can simulate the response of many climate variables, such as increases in global surface temperature and sea level, in various scenarios of greenhouse gas and other human-related emissions. (See Table 7.6.) The globally averaged surface air temperature increase from 1990 to 2100 for the range of IPCC-SRES scenarios is projected to be 1.4–5.8° Celsius. This increase would be without precedent during the last thousand years.

**Table 7.6 Observed and Modeled Changes in Extremes of Weather and Climate** *(IPCC 2002)*

| Change | Observed (1950–2000) | Projections from Models (2050–2100) |
|---|---|---|
| Higher maximum temperatures and more hot days | nearly all land areas | most models |
| Increase of heat index | many land areas | most models |
| More intense precipitation events | many northern hemisphere mid- to high-latitude land areas | most models |
| Higher minimum temperatures and fewer cold days | virtually all land areas | most models |
| Fewer frost days | virtually all land areas | physically plausible based on increased minimum temperatures |
| Reduced diurnal temperature range | most land areas | most models |
| Summer continental drying | few areas | most models |
| Increase in tropical cyclone peak wind intensities | not observed, but very few analyses | some models |
| Increase in tropical cyclone mean and peak precipitation intensities | insufficient data | some models |

A coherent picture of regional climate change using regionalization techniques is not yet possible. However, based on recent global model simulations, it is likely that nearly all land areas will warm more rapidly than the global average, particularly those at high latitudes in the cold season. Most notable is the warming in the northern regions of North America and in northern and central Asia, which is in excess of 40% above the global-mean change. In contrast, the warming is less than the global-mean change in South and Southeast Asia in summer and southern South America in winter.

Globally averaged precipitation is projected to increase. Based on recent global model simulations, it is likely that precipitation will increase over northern mid- and high latitudes and over Antarctica in winter. At low latitudes, there are both regional increases and decreases, which are likely to depend on the emissions scenario, but in general most arid and semiarid areas are projected to become drier.

Analyses of past data and improvements in climate models have enabled changes in extreme events observed to date (such as heat waves, heavy precipitation events, and droughts) to be compared to similar changes in model simulations for future climate.

For some other extreme phenomena, many of which may have important impacts on ecosystems and society, there is currently insufficient information to assess recent trends, and the confidence in models and understanding is inadequate to make firm projections on, for instance, the intensity of mid-latitude storms. Further, very small-scale phenomena, such as thunderstorms, tornadoes, hail, and lightning, are not simulated in global models. Recent trends for conditions to become more El Niño-like in the tropical Pacific are projected to continue in many models, although confidence in such projections is tempered by some shortcomings in how well El Niño is simulated in global climate models.

Northern Hemisphere snow cover and sea-ice extent are projected to decrease further. Glaciers and icecaps (excluding the ice sheets of Greenland and Antarctica) will continue their widespread retreat during the twenty-first century.

For the range of IPCC-SRES scenarios, a sea level rise of 9–88 centimeters is projected for 1990 to 2100, with a central value of 0.47 meters, which is about two to four times the rate over the twentieth century.

#### *7.3.1.5 Climate Drivers and Ecosystem Consequences*

Climate change and elevated atmospheric concentrations of $CO_2$ are projected to affect individuals, populations, species, and ecosystem composition and function both directly (through increases in temperature and changes in precipitation, changes in extreme climatic events and in the case of aquatic systems changes in water temperature, sea level, and so on) and indirectly (through climate changing the intensity and frequency of disturbances such as wildfires and major storms). The magnitude of the impacts will, however, depend on other anthropogenic pressures, particularly increased land use intensity and the associated modification, fragmentation, and loss of habitats (or habitat unification, especially in the case of freshwater bodies); the introduction of invasive species; and direct effects on reproduction, dominance, and survival through chemical and mechanical treatments.

No realistic projection of the future state of Earth's ecosystems can be made without taking into account all of these pressures—past, present, and future. Independent of climate change, biodiversity is forecast to decrease in the future due to the multiple pressures from human activities—climate change constitutes an additional pressure. Quantification of the impacts of climate change alone, given the multiple and interactive pressures acting on Earth's ecosystems, is difficult and likely to vary regionally.

The general impact of climate change is that the habitats of many species will move poleward or to higher elevations from their current locations, with the most rapid changes being where the general tendency is accelerated by changes in natural and anthropogenic disturbance patterns. For example, the climatic zones suitable for temperate and boreal plant species may be displaced by 200–1,200 kilometers poleward over the next 100 years. Weedy species (those that are highly mobile and can establish quickly) and invasive species will have advantage over others. Drought and desertification processes will result in movements of habitats of many species toward areas of higher rainfall from their current locations.

Species and ecosystems are projected to be affected by extreme climatic events—for example, higher maximum temperatures, more hot days, and heat waves are projected to increase heat stress in plants and animals and reduce plant productivity. Higher minimum temperatures, fewer cold days, frost days, and cold waves could result in an extended range and activity of some pest and disease vectors and increased productivity in some plant species and ecosystems. More-intense precipitation events are projected to result in increased soil erosion, increased flood runoff. Increased summer drying over most mid-latitude continental interiors and associated risk of drought are projected to result in decreased plant productivity, increased risk of wild fires and diseases, and pest outbreaks. Increased Asian summer monsoon precipitation variability and increased intensity of mid-latitude storms could lead to increased frequency and intensity of floods and damage to coastal areas.

#### *7.3.1.6 Overview of Climate Drivers in the MA Scenarios*

The MA scenarios use the IPCC-SRES scenarios as a basis for their assumptions about the energy and climate developments. The range of climate drivers in the MA scenarios can be found in Chapter 9.

### 7.3.2 Plant Nutrient Use

All plants require three macronutrients—nitrogen, phosphorus, and potassium—and numerous micronutrients for growth. Crop production often requires supplementation of natural sources. Nitrogen and phosphorus can move beyond the bounds of the field to which they are applied, potentially affecting ecosystems offsite. In addition, phosphorus used in detergents and output from sewer systems has been an important contributor to aquatic plant growth in water bodies near population centers in some parts of the world. In this section, we focus on nitrogen and phosphorus as drivers of ecosystem changes. Potassium is relatively immobile and mostly benign offsite, so it is not discussed. Other nutrients, particularly micronutrients, are of great importance in many parts of the world as drivers for sustainable crop production and human health (Welch and Graham 1999). Finally, carbon is itself a fertilizer, and rising carbon concentrations, especially the upper range across IPCC-SRES emissions scenarios, would also affect growth of plants.

#### *7.3.2.1 Nitrogen Use and Trends*

Atmospheric N is mostly inert $N_2$ gas, which is fixed into reactive, biologically available forms through both natural and anthropogenic fixation processes. Human activities are dramatically changing the rate of $N_2$ fixation and global atmospheric deposition of reactive N (Galloway and Cowling 2002). Reactive N is defined as all biologically, photochemically, or radiatively active forms of N, a diverse pool that includes mineral N forms such as $NO_3^-$ and $NH_4^+$, gases that are chemically active in the troposphere ($NO_x$ and $NH_3$), and gases such as $N_2O$ that contribute to the greenhouse effect (Galloway et al. 1995). In 1990, the total amount of reactive N created by human activities was about 141 teragram N per year (see Table 7.7), which represents a ninefold increase over 1890, compared with a 3.5-fold increase in global population (Galloway and Cowling 2002). Between 1960 and 2002, use of nitrogenous fertilizers increased eightfold, from 10.83 million to 85.11 million tons of nitrogen (IFA 2004).

In the past, creation of reactive N was dominated by natural processes, which also increased forest biomass production and storage of atmospheric $CO_2$ in plant and soils (Mosier et al. 2001) At present, biological $N_2$ fixation occurring in cultivated crops, synthetic N production through the Haber-Bosch process, and fossil-fuel combustion have become major sources of reactive N (Galloway and Cowling 2002). Vitousek et al. (1997) estimate that humans have approximately doubled the rate of N input to the terrestrial N cycle.

**Table 7.7 Regional Creation of Reactive Nitrogen in the Mid-1990s** (Galloway and Cowling 2002)

| World Regions | Reactive Nitrogen Creation | |
|---|---|---|
| | Total (teragram per year) | Per Person (kilogram per year) |
| Africa | 5.3 | 7 |
| Asia | 68.9 | 17 |
| Europe and former Soviet Union | 26.5 | 44 |
| Latin America | 9.4 | 19 |
| North America | 28.4 | 100 |
| Oceania | 2.2 | 63 |
| World | 140.7 | 24 |

Large regional differences in reactive N creation occur. Whereas Asia accounts for nearly 50% of the net global creation of reactive N, per capita creation is by far largest in North America, followed by Oceania and Europe. Inorganic fertilizers contribute about 82 teragram N per year reactive N, whereas managed biofixation adds about 20 teragram N per year and recycling of organic wastes 28–36 teragram N per year (Smil 1999).

It is generally believed that organic nutrient sources offer environmental and other benefits, but the potential benefits from relying on organic sources must be weighed against potential limitations (Cassman et al. 2003). Although demand for organic food is predicted to grow, especially in higher-income countries, only 1% of the world's cropland (about 16 million hectares) is currently under certified organic production (FAO 2002). Globally, organic N sources are not available in amounts that would be large enough to meet nutrient needs for food production. On a global basis, manure and legumes can contribute about 25% of crop N requirements (Roy et al. 2002). Except for soybeans, however, legume area is declining worldwide, and this trend is unlikely to be reversed in the near future (Smil 1997). Moreover, controlling the fate of N from organic sources is as difficult as managing the fate of N from mineral fertilizer. Organic or low-input agriculture alone cannot secure the future food supply in the developing world, where maintaining low food prices contributes to reducing poverty and increasing economic wealth (Senauer and Sur 2001).

Crop production at a global scale will largely depend on mineral N fertilizer to meet current and future food demand (Cassman et al. 2003). Nitrogen use in developing countries has increased exponentially during the course of the Green Revolution (see Figure 7.16 in Appendix A) due to rapid adoption of improved high-yielding varieties that could respond to the increased N supply and greater cropping intensity (Cassman and Pingali 1995). In industrial countries, excluding Eastern Europe and the former Soviet Union, N fertilizer use has remained relatively constant during the past 25 years, although yields of many crops continue to rise slowly. In Eastern Europe and the countries of the former Soviet Union, N consumption dropped in the 1990s as a result of political and economic turmoil.

The three major cereals—maize, rice, and wheat—account for about 56% of global N fertilizer use (IFA 2002). At a global scale, cereal yields and fertilizer N consumption have increased in a near-linear fashion during the past 40 years and are highly correlated with one another. The ratio of global cereal production to global fertilizer N consumption shows a curvilinear decline in the past 40 years, raising concerns that future increases in N fertilizer use are unlikely to be as effective in raising yields as in the past (Tilman et al. 2002). Because the relationship between crop yield and N uptake is tightly conserved (Cassman et al. 2002), achieving further increases in food production will require greater N uptake by crops and, consequently, either more external N inputs or more efficient use of N. Recent estimates for major cereals suggest that increases in N consumption by about 20–60% during the next 25 years will be required to keep pace with the expected demand (Cassman et al. 2003).

Agricultural lands lose a substantial fraction of the fertilizer N applied, often 40–60%. Therefore, enhancing the efficiency of N use from fertilizer (nitrogen use efficiency) is a key measure for reducing the amount of reactive N released into ecosystems (Galloway et al. 2002). The simplest measure of NUE is the amount of grain (or other harvest product) produced per unit N input, which is an aggregate efficiency index that incorporates the contributions from indigenous soil N, fertilizer uptake efficiency, and the efficiency with which N acquired by the plant is converted into grain yield.

Large differences in NUE exist among countries, regions, farms, fields within a farm, and crop species, because crop yield response functions to N vary widely among different environments (Cassman et al. 2002). Therefore, policies that promote an increase or decrease in N fertilizer use at state, national, or regional levels would have a widely varying impact on NUE, yields, farm profitability, and environmental quality.

Large-scale NUE can be increased with sufficient investments in research and policies that favor increases in NUE at the field scale. Figure 7.17 shows that in U.S. maize systems, NUE increased from 42 kilograms of crop per kilogram of N in 1980 to 57 kilograms of crop in 2000 (Cassman et al. 2002). Three factors contributed to this improvement: increased yields and more vigorous crop growth associated with greater stress tolerance of hybrids (Duvick and Cassman 1999); improved management of production factors other than N (conservation tillage, seed quality and higher plant densities); and improved N fertilizer management (Dobermann and Cassman 2002).

In Japan, NUE of rice remained virtually constant at about 57 kilograms of crop per kilogram N from 1961 to 1985, but this has increased to more than 75 kilograms of

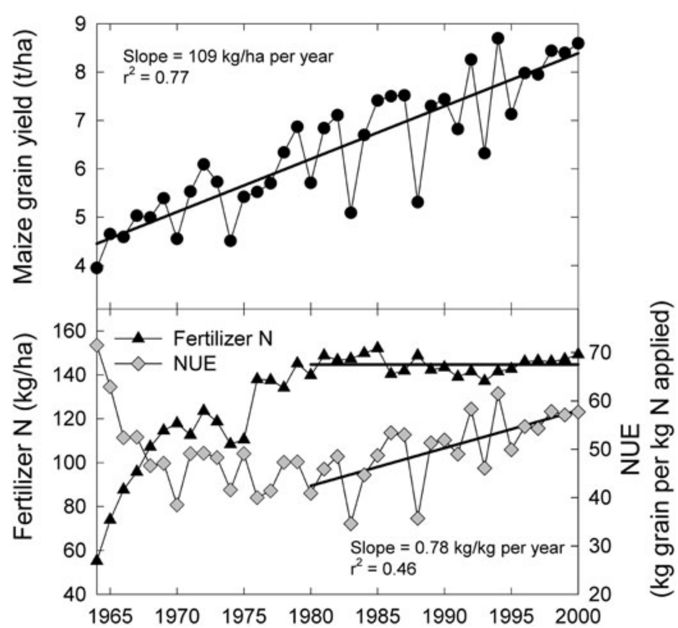


**Figure 7.17. Trends in Maize Grain Yield, Use of Nitrogen Fertilizer, and Nitrogen Use Efficiency in United States, 1965–2000** (modified from Cassman et al. 2002)

crop in recent years (Mishima 2001). Key factors contributing to this increase were a shift to rice varieties with better grain quality, which also had lower yield potential and nitrogen concentrations, and the adoption of more knowledge-intensive N management technologies (Suzuki 1998).

Increasing NUE in the developing world presents a greater challenge. Nitrogen use efficiency is particularly low in intensive irrigated rice systems of sub-tropical and tropical Asia, where it has remained virtually unchanged during the past 20–30 years (Dobermann and Cassman 2002). Research has demonstrated, however, that rice is capable of taking up fertilizer N very efficiently provided the timing of N applications is congruent with the dynamics of soil N supply and crop N demand (Peng and Cassman 1998). These principles have recently become embedded in a new approach for site-specific nutrient management, resulting in significant increases in yields and NUE at numerous farms sites across Asia (Dobermann et al. 2002). Improving the congruence between crop N demand and N supply also was found to substantially increase N fertilizer efficiency of irrigated wheat in Mexico (Matson et al. 1998; Riley et al. 2003).

#### *7.3.2.2 Phosphorus Use and Trends*

Phosphorus is widely used in fertilizers for agricultural crops, as well as on lawns in high-income countries. It is also used as a nutrient in supplements for dairy cattle in some parts of the world. More than 99% of all phosphate fertilizers are derived from mined phosphate rock. Just six countries account for 80% of the world phosphate rock production (United States Geological Survey 2003): the United States (27% of world total), Morocco and Western Sahara (18%), China (16%), Russia (8%), Tunisia (6%), and Jordan (5%). At current annual mining rates of 133 million tons per year, known phosphate rock reserves and resources would last for about 125 and 375 years, respectively (United States Geological Survey 2003).

Globally, fertilizer-P consumption, which rose steadily from 1961 to the late 1980s, appears to have leveled off around 33 million tons after a drop in the early 1990s, but regional differences occur. (See Figure 7.18 in Appendix A.) Phosphorus consumption has steadily declined since the late 1970s in higher-income countries, whereas it continues to rise in many lower-income countries, particularly in Asia. Phosphorus consumption dropped sharply in the 1990s in Eastern Europe and the former Soviet Union, which is likely to cause a drawdown of soil P resources in these regions. China, Brazil, India, and the United States are currently the major consumers of phosphate fertilizers. Fertilizer P use has remained low in many poor countries of Africa and other parts of the world.

Livestock excreta play an important role in the global P cycle. Recent estimates suggest that the total amount of P contained in livestock excreta was 21 million tons in 1996, of which 8.8 million tons were recovered in manure (Sheldrick et al. 2003a). However, manure P input has declined from 50% of the fertilizer plus manure P input in 1961 to 38% in 1996 (Sheldrick et al. 2003a).

Global agricultural P budgets (inputs are fertilizers and manures and outputs are agricultural products and runoff) indicate that average P accumulation in agricultural areas of the world is approximately 8 million tons P per year. While P is still accumulating, the rate of annual accumulation has begun to plateau, possibly as early as the 1980s. (See Figure 7.19.) Slowing rates of annual accumulation is causing the rate of increase in cumulative accumulation to decline, but this decline (2–4 million tons P per year) is minimal compared with total cumulative accumulation (over 300 million tons P per year).

P accretion is occurring in many countries, but rates of P accumulation over time vary. (See Figure 7.20.) On average, rates of P accumulation on agricultural land have

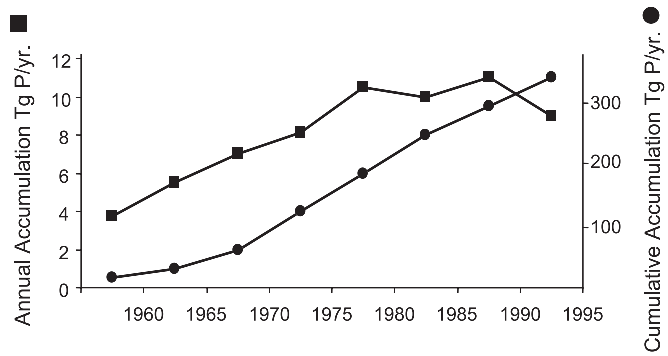


**Figure 7.19. Phosphorus Accumulation in Agricultural Soils, 1960–95, as Determined by Global Budget.** Squares indicate annual accumulation based on five-year averages. Circles represent cumulative P accumulation. Inputs are fertilizer and manure, based on global estimates of fertilizer use from the FAO 1950–97 and estimates of manure production based on animal densities. Outputs are agricultural products such as meat, eggs, and grains based on agricultural production data from FAO 1950–98, and the percentage P of those products and P in runoff. (Bennett et al. 2001)

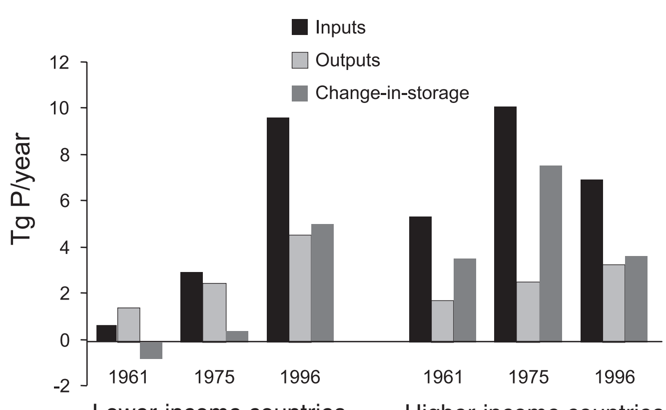


**Figure 7.20. Estimated Inputs, Outputs, and Change in Storage of Phosphorus on Agricultural Lands in Lower- and Higher-income Countries, 1961–96.** Inputs include fertilizers and manure; outputs are runoff and crops harvested. Note that the drop in fertilizer use in the industrial countries in 1996 may be due to greatly reduced fertilizer use in the Former Soviet Union and Eastern Europe. (Bennett et al. 2001)

started to decline in higher-income countries but are still rising in lower-income ones. While agricultural lands in the latter had a net loss of P in 1961, they now accumulate more phosphorus per year than do higher-income countries' agricultural areas, making up 5 million of the 8 million tons per year total global P accumulation on agricultural lands. This accumulation is a global average; actual accumulation will vary at regional, national, and local scales.

Calculating nutrient budgets is associated with many uncertainties that are seldom taken into account (Oenema et al. 2003). Many estimates are partial budgets or include numerous assumptions about components that are difficult to quantify at the scales of interest. Moreover, great diversity exists in P budgets among countries, within a country, or even between fields in the same farm. Nutrient audits for China suggest average annual P losses of 5 kilograms per hectare of agricultural land (Sheldrick et al. 2003b). Similarly, an annual loss of 3 kilograms of phosphorus per hectare was estimated for 38 countries of sub-Saharan Africa (Stoorvogel et al. 1993).

In contrast, on-farm studies conducted at 207 sites in China, India, Indonesia, Thailand, and the Philippines showed an average annual surplus of 12 kilograms P per hectare under double-cropping of irrigated rice (Dobermann and Cassman 2002). A study in Uganda demonstrated that the P balance was near neutral for a whole district, but it varied from positive in fields near homesteads to negative in outfields (Bekunda and Manzi 2003). In Southern Mali, P was at balance for the whole region, but large local variations occurred (Van der Pol and Traore 1993). Soil surface P balances studied in nine organic farms in the United Kingdom were positive in six cases, resulting from supplementary P fertilizer (rock phosphate) and additional feed for non-ruminant livestock, whereas a stockless system without P fertilizer resulted in a large P deficit (Berry et al. 2003). In slash-and-burn agriculture, the P balance is only positive when fertilizer is applied (Hoelscher et al. 1996).

Global differences in soil quality also affect the relationships between fertilizer P use, crop productivity, and risk of P pollution. In many tropical regions, small farmers operate on acid upland soils with high P-fixation potential. Reclamation of P-deficient land requires larger phosphate applications (Uexkuell and Mutert 1995) and good soil conservation to prevent P losses by erosion.

### *7.3.2.3 Potassium Use and Trends*

Annual global potash production amounts to about 26 million tons, of which 93% is used in agriculture. Roughly 96% of all potash is produced in North America, Western and Eastern Europe, and the Middle East. Nine companies in Canada, Russia, Belarus, Germany, the United States, and Israel account for 87% of the global potash production. Large amounts of potash fertilizers are shipped around the globe to satisfy the needs of crop production for this important macronutrient.

Trends in global potash fertilizer use are similar to those observed for N and P: stagnating or slightly declining use in many higher-income countries, significant increases in selected lower-income countries, and a sharp drop in Eastern Europe and the former Soviet Union in recent years. (See Figure 7.21.)

Negative potassium (or K) budgets in many parts of the developing world raise concern about the long-term sustainability of crop production, particularly under intensive cultivation. For example, although K use has increased on agricultural land in China during the past 20 years, the nation's overall annual K budget remains highly negative at about negative 60 kilograms per hectare (Sheldrick et al. 2003b). Similar estimates for India and Indonesia suggest annual K losses of about 20–40 kilograms of K per hectare, and these losses have been increasing steadily during the past 40 years. An average annual K loss of nearly 20 kilograms per hectare was estimated for all of sub-Saharan Africa (Stoorvogel et al. 1993). Average annual K losses of about 50 kilograms per hectare are common in double cropping rice systems of Asia (Dobermann et al. 1998).

Overall, potassium deficiency in agriculture is not yet widespread, but if present trends continue, it is only a matter of time until depletion of soil K resources will reach levels that could cause significant limitations for crop production. Because most of the K taken up by plants is contained in vegetative plant parts, recycling of crop residue and organic wastes is a key issue for sustaining K input-output balances. Mineral fertilizer use must be balanced with regard to K, which is an important measure to increase yields and nitrogen use efficiency. To achieve this, annual rates of K use in the developing world may have to rise much faster than those of N use.

### *7.3.2.4 Plant Nutrient Drivers and Ecosystem Consequences*

#### *7.3.2.4.1 Nitrogen and ecosystem consequences*

Synthetic production of fertilizer N has been a key driver of the remarkable increase in food production that has occurred during the past 50 years (Smil 2001), but crop production also contributes much to global accumulation of reactive N. Only about half of all anthropogenic N inputs on croplands are taken up by harvested crops and their resi-

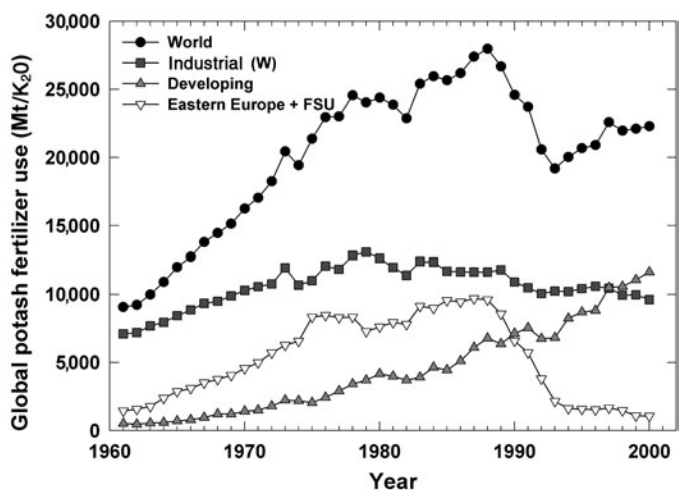


**Figure 7.21. Trends in Global Consumption of Potash Fertilizer, 1961–2000** (IFA 2003)

dues. Losses to the atmosphere amount to 26–60 million tons N per year, while waters receive 32–45 million tons N per year from leaching and erosion (Smil 1999). Many uncertainties are associated with these estimates, but there is increasing concern about the enrichment of the biosphere with reactive N forms and significant changes in reactive N distribution (Galloway and Cowling 2002). The key challenge is to meet the greater N requirements of higher-yielding crops while concurrently increasing nitrogen use efficiency and reducing the reactive N load attributable to agriculture.

If left unchecked, significant costs to society may arise through both direct and indirect effects on the environment and human health (Wolfe and Patz 2002) caused by increased emissions of $NO_x$, $NH_3$, $N_2O$, $NO_3$, and dissolved organic N compounds or by deposition of $NO_y$ and $NH_x$ compounds (Mosier et al. 2001; Townsend et al. 2003). Consequences include decreased drinking water quality (Spalding and Exner 1993), eutrophication of freshwater ecosystems (McIsaac et al. 2001), hypoxia in coastal marine ecosystems (Rabalais 2002), nitrous oxide emissions contributing to global climate change (Smith et al. 1997; Bouwman et al. 2002), and air pollution by $NO_x$ in urban areas (Townsend et al. 2003). Occurrence of such problems varies widely in different world regions. However, preliminary estimates for the United Kingdom (Pretty et al. 2000) and Germany (Schweigert and van der Ploeg 2000) suggest that the environmental costs of excessive N fertilizer use may be a substantial proportion of the value of all farm goods produced.

##### *7.3.2.4.2 Phosphorus and ecosystem consequences*

Approximately 20–30% of P in fertilizer is taken up by agricultural plants when they grow (Sharpley et al. 1993). The remainder accumulates in the soil or runs off. Phosphorus moves downhill in particulate or dissolved form, where it has secondary impacts on other ecosystems.

Phosphorus is the limiting nutrient in most freshwater lakes (Vollenweider 1968; Schindler 1977) and is a critical nutrient in the productivity of marine ecosystems (Tyrell 1999). Excess P degrades lakes through a syndrome of increased productivity called eutrophication (Vollenweider 1968; Schindler et al. 1971; Dillon and Rigler 1974). Phosphorus is the primary cause of most freshwater eutrophication and a component of estuarine eutrophication. Eutrophic lakes frequently experience noxious algal blooms, increased aquatic plant growth, and oxygen depletion, leading to degradation of their ecological, economic, and aesthetic value by restricting use for fisheries, drinking water, industry, and recreation (National Research Council 1992; Sharpley et al. 1994).

When lakes become eutrophic, many ecosystem services are reduced. Water from lakes that experience algal blooms is more expensive to purify for drinking or other industrial uses (Carpenter et al. 1998). Eutrophication can also restrict use of lakes for fisheries because low oxygen levels reduce fish populations (Smith 1998). While habitat for some aquatic plants, such as noxious algae, are increased by eutrophication, habitat for other plants, such as aquatic macrophytes, may decrease. Underlying all these changes are reductions in some of the supporting services provided by lakes, such as nutrient cycling. Possibly the most striking loss is that of many of the cultural services provided by lakes. Foul odors of rotting algae, slime-covered lakes, and toxic chemicals produced by some blue-green algae during blooms keep people from swimming, boating, and otherwise enjoying the aesthetic value of lakes.

In marine systems, excess P input causes harmful algal blooms (including blooms of toxic species); growth of attached algae and macrophytes that can damage benthic habitats, including coral reefs; problems with deoxygenation and foul odors; fish mortality; and economic losses associated with increased costs of water purification and impairment of water supply for agriculture, industry, and municipal consumption (Postel 1997; Carpenter et al. 1998; Smith 1998). The U.S. Environmental Protection Agency called eutrophication the most ubiquitous water quality problem in the United States (U.S. Environmental Protection Agency 1996). Although it is currently a key problem primarily in industrial countries with high rates of fertilizer use, recent increases in phosphate fertilizer use in developing countries indicate that it may become of increasing importance there as well.

It is extremely difficult to control P runoff because it comes from widely dispersed sources and can vary with weather. Studies indicate that agriculture is a major source of P (Sharpley 1995) and that most of the runoff happens during spring storms that carry soils and their P into bodies of water (Pionke et al. 1997), but it has proved very difficult to locate particular fields as important sources in ways other than through proxy measurements, such as high concentrations of P in the soil.

Accumulation of P uphill from bodies of water has been termed a chemical time bomb (Stigliani et al. 1991) because it is simply waiting to be transported to downstream water bodies through erosion and other processes. As a global average, if we completely ceased all P fertilizer use it would take approximately 40 years for soil P concentrations to return to 1958 levels (calculated based on Bennett et al. 2001). It is important to keep in mind that turnover rates for P in soils are highly variable in space. Some areas with high soil P may have very slow turnover. For example, a study of the Lake Mendota watershed in Wisconsin USA, suggests that if over fertilizing were to stop, it would still take over 260 years for P in the soil to drop to 1974 levels (Bennett et al. 1999). Other budgets for high P soils indicate similarly long turnover times. However, many regions, especially in highly weathered tropical soils, have soils that are very impoverished in P and would have a shorter drawdown time.

##### *7.3.2.4.3 Potassium and ecosystem consequences*

Negative environmental impacts of potassium are negligible, so that its major role as an ecosystem driver is that of increasing crop productivity. Potassium has no known negative consequences for ecosystems, and its excessive accumulation in soils and waters is rare.

#### *7.3.2.5 Summary of Plant Nutrient Drivers*

Human activities have dramatically altered plant nutrient cycles. Human interventions have had a positive impact on crucial ecosystem services such as food supply but have also caused numerous negative consequences for other ecosystem services. These impacts (negative and positive) vary by location.

Changes in the global atmospheric deposition of reactive N and in the concentrations of soil P have had a positive impact on increasing food production at affordable prices but have also had negative consequences for some ecosystem services. Traditional cropping practiced before synthetic N fertilizers became available could provide today's average diets for only about 40% of the existing population (Smil 2001). As the human population continues to increase, fertilizer N will continue to play a dominant role in the global N cycle. Therefore, increases in nitrogen use efficiency are necessary to control the cycling of the most potent reactive N compounds. There is much potential for fine-tuning N management in agricultural crops through technologies that achieve greater congruence between crop N demand and N supply from all sources—including fertilizer, organic inputs, and indigenous soil N (Cassman et al. 2002). Such improvements are likely to have a large impact on the global N cycle, but they require collaboration among agronomists, soil scientists, agricultural economists, ecologists, and politicians (Galloway et al. 2002), as well as significant long-term investments in research and education.

Patterns of P supply, consumption, and waste production have also become decoupled from natural P cycles (Tiessen 1995). Changing the P cycle has had a positive impact on production of food from agricultural areas, but a negative impact on provision of services from aquatic ecosystems downstream from those areas. Phosphorus surpluses due to fertilizer use, livestock industry, and imports of feed and food have become widespread in high-income countries. In contrast, both P surpluses and deficits are found in developing countries, including large areas that are naturally P-deficient. Finding ways to maintain or increase agricultural production without sacrificing water quality will be a major issue in the coming years.

#### *7.3.2.6 Overview of Plant Nutrient Drivers in the MA Scenarios*

Changes in nutrient use vary among the scenarios, depending on the key indirect drivers of food demand and technological change. Increased food demand generally leads to increases in the amount of fertilizer used; however, this can be tempered by technological change that results in increased food production without additional fertilizers.

All scenarios will experience some increase in the use of N and P fertilizers due to growing human population and increased demand for food. Global Orchestration is projected to have the highest increase in fertilizer use. Increasing economic openness in this scenario makes fertilizers available in locations where they currently are not commonly used. Much of the increase in fertilizer use will be in currently poor countries. Order from Strength will also have a large increase in fertilizer use. In this scenario, however, most of the increase comes from higher use in wealthier countries.

Increased agricultural production in wealthier countries requires increased efficiency of production from lands already in cultivation in addition to a greater amount of cultivated land. Without additional technological advances, production is likely to be improved through heavier use of fertilizers. Food production in the TechnoGarden scenario also increases, but technical change is the primary driver, so fertilizer use increase is the lowest in this scenario. Nutrient use in the Adapting Mosaic scenario falls in the range of the other scenarios. The environmentally proactive approach should lead to decreased use of fertilizers, but low amounts of trade will force people in some areas to use fertilizers heavily simply to feed people locally.

### 7.3.3 Land Conversion

Humans change land use to alter the mix of ecosystem services provided by that land. Sometimes the land conversion effort is intentional, such as plowing grassland to grow crops. In other cases, land conversion is a consequence of other activities. For example, salinization is the unintended consequence of irrigation that does not have adequate drainage.

The Millennium Ecosystem Assessment sponsored an international effort to document regions around the world in which rapid and recent change (since the 1970s) in land cover can be shown to have occurred (Lepers et al. in press). In this section, we summarize its results, focusing on four types of land conversion—deforestation, dryland degradation, agricultural expansion and abandonment, and urban expansion.

#### *7.3.3.1 Deforestation*

Deforestation is the single most measured process of land cover change at a global scale (FAO 2001a; Achard et al. 2002; DeFries et al. 2002). According to most definitions, a forest is defined as land with tree canopy cover above some minimum threshold or as land that is intended to be used as forested land. (Different thresholds have been used to define forested land; for instance FAO (2001a) uses a 10% tree canopy cover threshold, whereas the IGBP land-cover classification uses a 60% threshold (Scepan 1999).) Deforestation occurs when forest is converted to another land cover and intended land use. Not all disturbances in a forest ecosystem lead to deforestation. Forested land that has been harvested and has not yet regrown to forest is often still categorized as forest in many databases. Forest degradation—"changes within the forest that negatively affect the structure or function of the stand or site and thereby lower the capacity to supply products and/or services"—can but does not necessarily lead to deforestation (FAO 2001a).

Afforestation is the conversion from some other land use to forest; reforestation is afforestation on land that at some point in the past was forested. Data on afforestation and reforestation are much less readily available than on deforestation. Few spatially explicit data sets on afforestation, forest expansion, or reforestation were found in the literature at a regional scale, even though these positive changes in forest represent a major ecosystem change and should not be ignored (see Munroe et al. 2002 for an example of a region of Honduras where both deforestation and reforestation have occurred, and additional references in Turner II et al. 2004). According to FAO (2001a), global forest area underwent a net change of −9.4% between 1990 and 2000. Losses of 16.1% were balanced by a 6.7% gain in forest area (mainly forest plantations or regrowth). The latter figures suggest that the extent of afforestation is considerable.

Remotely sensed data can often be used to distinguish between forested and nonforested land. Three quarters of the world's forests are covered by at least one remote sensing–based or expert-opinion data set on the occurrence of deforestation or degradation. Approximately 8% of the forests are covered by five data sets, with coverage in the Amazon Basin being especially extensive. On the other hand, one quarter of the world's forests only have statistical information on deforestation at national or sub-national scales. This is the case, for instance, for Europe and Canada.

Using the forest classes of the GLC 2000 and IGBP DIScover data sets, forests covered 39% of Earth's surface in 2000. Around 30% of the world's forests were located in Asia. Africa, South America, and North America (Canada, the United States, and Mexico) each accounted for less than 20% in 2000.

As noted in Chapter 21 of the MA *Current State and Trends* volume, during the industrial era, global forest area was reduced by 40%, with three quarters of this loss occurring during the last two centuries. Forests have completely disappeared in 25 countries, and another 29 have lost more than 90%. Although forest cover and biomass in Europe and North America is currently increasing following radical declines in the past, deforestation of natural forests in the tropics continues at an annual rate of over 10 million hectares a year—an area larger than Greece, Nicaragua, or Nepal, and more than four times the size of Belgium. Moreover, degradation and fragmentation of remaining forests are further impairing ecosystem functioning. The area of planted forests is, however, growing, decreasing the likelihood of a global shortage of wood.

Existing data suggest that deforestation and forest degradation have been more extensive in the tropics than in the rest of the world, but this is possibly due to the fact that most data sets cover the tropics and not the boreal zones. Only 20% of the forests of nontropical areas are covered by at least one remote sensing–based or expert-opinion data set, while the entire tropical region is covered. Areas of deforestation or degradation may thus go uncounted in the boreal or temperate regions. Some locations in Canada and Europe are also subject to intensive forest exploitation and could also appear as degraded as Siberia.

#### *7.3.3.2 Dryland Degradation*

Drylands are defined in the World Atlas of Desertification as zones having a ratio of average annual precipitation to potential evapotranspiration lower than 0.65 (Middleton and Thomas 1997). Dryland degradation, also called desertification, has affected parts of Africa, Asia, and Mediterranean Europe for centuries, parts of America for one or two centuries, and parts of Australia for 100 years or less (Dregne 2002).

There is little agreement on the definition and indicators of desertification, so this category of land cover change is not easy to map at a global scale. The most commonly accepted definition of desertification is ''land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities'' (UNCED 1992). In the UNCED definition from *Agenda 21,* desertification only applies to the drylands of the world. Hyper-arid zones are not part of the definition because they are presumed to be so dry that human degradation is severely limited unless irrigation is practiced. But they are included in the statistics reported here as well as in Chapter 22 of the *Current State and Trends* volume.

Despite the global importance of desertification, available data on the extent of land degradation in drylands are extremely limited. To date, only two studies are available with global coverage. Both have considerable weakness, but for lack of anything better they are widely used as a basis for many national, regional, and global environmental assessments. The most well known study is the Global Assessment of Soil Degradation, or GLASOD (Oldeman et al. 1991). This study found that 20% of the world's drylands (excluding hyper-arid areas) suffered from soil degradation. Water and wind erosion was reported as the prime cause for 87% of the degraded land (Thomas and Middleton 1997; Oldeman and van Lynden 1997).

The second global study is that of Dregne and Chou (1992), which covered both soil and vegetation degradation. It was based on secondary sources, which they qualified as follows: ''The information base upon which the estimates in this report were made is poor. Anecdotal accounts, research reports, travelers' descriptions, personal opinions, and local experience provided most of the evidence for the various estimates.'' This study reported that some 70% of the world's drylands (excluding hyper-arid areas) were suffering from desertification (soil and vegetation degradation).

The MA-commissioned study by Lepers et al. (in press) compiled more detailed (sometimes overlapping) regional data sets (including hyper-arid drylands) derived from literature review, erosion models, field assessments, and remote sensing. The data sets used to assess degradation covered 62% of the drylands of the world. Major gaps in coverage occurred around the Mediterranean Basin, in the Sahel, in the east of Africa, in parts of South America (north of Argentina, Paraguay, Bolivia, Peru, and Ecuador), and in the federal lands of the United States. This study found less alarming levels of land degradation (soil plus vegetation) in the drylands and hyper-arid regions of the world. With only partial coverage, and in some areas relying on a single data set, it estimated that 10% of global drylands were degraded.

#### *7.3.3.3 Agricultural Conversion*

Most of the studies and data sets related to changes in agricultural land focus on changes in arable land and permanent crops. As defined by FAO, arable land refers to land under temporary crops, temporary meadows for mowing or pasture, land under market and kitchen gardens, and land temporarily fallow (less than five years). Permanent crop represents land cultivated with crops that occupy the land for long periods and need not be replanted after each harvest, such as cocoa, coffee, and rubber. This category includes land under flowering shrubs, fruit trees, nut trees, and vines but excludes land under trees grown for wood or timber (FAO 2001b). As defined by FAO, agricultural land also includes permanent pasture. However, this category of land use was not included here due to lack of data and the difficulty of differentiating pastures from natural unmanaged grasslands in many parts of the world. So the term ''cropland class,'' as used here, refers to arable land and permanent crops.

The cropland class, defined as areas with at least 10% of croplands within each pixel, covered 30% of Earth's surface in 1990. The exact proportion was between 12% and 14%, depending on whether Antarctica and Greenland were included (Ramankutty and Foley 1998). Around 40% of the cropland class was located in Asia; Europe accounted for 16% and Africa, North America, and South America each accounted for 13%.

Lepers et al. (in press) attempted to assess the change in cropland area between 1980 and 1990 by combining data from a variety of sources and time periods. This effort resulted in unexpected outcomes, including extensive cropland increase in the central United States, southern Ireland, and the island of Java. It found conversely that cropland area decreased in China and that there no identifiable hotspots of cropland increase in the central part of Africa. Clearly, much more analysis is needed to identify changes in this critical driver of ecosystem change. (See Box 7.2 for a profile of land use change in one region.)

#### *7.3.3.4 Urbanization*

In 2000, towns and cities sheltered more than 2.7 billion of the world's 6 billion people (UNDP 2000). Growth in urban population usually results in conversion of agricultural, often highly productive land and other land types for residential, infrastructure, and amenity uses. These growing cities have an impact on their surrounding ecosystems through their demand for food, fuel, water, and other natural resources (Lambin et al. 2003).

So far no global data sets or direct measurements have been developed to delineate the changes in extent and shape of urban areas. Only indirect indicators such as human population or the evolution through time of the night-time lights viewed from space can be used as a proxy to measure the change in urban extent. The data presented here are based on such indirect indicators and should be considered tentative.

Global population is strongly clustered, with 50% of the world's population inhabiting less than 3% of the available land area (excluding Antarctica), at average densities greater than 300 people per square kilometer (Small 2001). Today's largest cities are mainly located on the eastern coast of the United States, in western Europe, in India, and in East Asia; the most rapidly growing cities are all located in the tropics.

### 7.3.4 Biological Invasions and Diseases

#### *7.3.4.1 Biological Invasions and Ecosystem Effects*

At present, no definition of biological invasion has been unanimously accepted by the scientific community, due in part to the proliferation of terms to describe various concepts used by different authors (Richardson et al. 2000). However, consensus is growing around at least two main aspects of the invasion process: the traits that enable a species to invade a habitat, called invasiveness, and the habitat characteristics that determine its susceptibility to the establishment and spread of an invasive species, its ''invasibility'' (Lonsdale 1999; Alpert et al. 2000).

This conceptual framework allows for an operational definition of invasive species as a species that spreads in space, either occupying new habitats or increasing its cover in areas previously occupied. This approach allows for a more general treatment of the invasion problem, since cases in which native species become invaders after some habitat or climatic change (for example, shrub encroachment, crayfish, and lampreys (Jeltsch et al.1997; Lodge et al. 2000; van Auken 2000)) can also be considered. Thus, although most of invasions are thought to be caused by non-native species, the key distinction becomes between invasive and noninvasive species rather than between native and non-native species (Crawley 1986; Alpert et al. 2000; Sakai et al. 2001).

Biological invasions are a global phenomenon, affecting ecosystems in most biomes (Mack et al. 2000). Human-driven movement of organisms, deliberate or accidental, has caused a massive alteration of species ranges, overwhelming the changes that occurred after the retreat of the last Ice Age (Semken 1983). Ecosystem changes brought about by invasions can have both short-term (ecological) and long-term (evolutionary) consequences. For example, the tropical alga *Caulerpa taxifolia* evolved tolerance for colder temperatures while it was growing in aquaria. After escaping, it is invading vast portions of the northwest Mediterranean Sea (Meisnesz 1999).

Ecological interactions between invaders and native species can be complex. Invaders can affect native species, but natives also affect performance of the invaders during the invasion process.

Acceleration of extinction rates as a result of negative interactions is one of the most important consequences of biological invasions (Ehrlich and Daily 1993; Daily and Ehrlich 1997; Hughes et al. 1998). In the United States, invasions of non-native plants, animals, and microbes are thought to be responsible for 42% of the decline of native species now listed as endangered or threatened (Pimentel 2002).

In some cases, the invader causes inhibition of the establishment of native species (a kind of ammensalism) (Walker and Vitousek 1991). Cases of commensalism and mutualism are less well documented. (Symbiosis is a mutually beneficial relationship between two organisms; commensalism is a relationship in which only one of the two organisms ob-

BOX 7.2
**Drivers of Land Use Change in Central Asia**

The Central Asian region consists of a broad range of ecosystems and associated land uses, spanning an area from west of the Urals to the Mongolian Plateau and the forests of the Far East of Russia. Historically, this region has been an important supplier of meat, milk, wool, forest products, and grains. Low population densities of nomadic pastoralists in most of this region used the rich grasslands to graze mixed herds of cattle, sheep, goats, horses, and camels. Grazing patterns were dictated more by intra- and interannual climate variability than political or economic factors.

Political and social changes have lead to dramatic adjustments in land use. During the early 1900s, most croplands and livestock systems were placed under collective management and remained there until the dissolution of the Soviet Union. These land use policies led to major changes in land management throughout the region and altered the transhumance patterns of livestock and rangeland management. Many aspects of the traditional nomadic culture were replaced. The largest decline in world forests and grassland areas in the past two centuries took place in the Eurasian region. Large-scale agricultural intensification took place during the Soviet era, and livestock production was made more sedentary. Cropland conversion peaked during the late 1980s.

Land degradation due to overgrazing, sowing of monocultures, poor irrigation management, cropping marginal lands, and increased frequency of fires has become a serious environmental concern. UNEP estimates that 60–70% of the grasslands in China, Mongolia, Central Asia, and Russia are overgrazed or degraded due to inappropriate cropping.

The dissolution of the Soviet Union led to changing pressures on land use once again. Since 1990, land managers have been adjusting to life in transition economies, characterized by a combination of volatile markets, policy changes, reductions in public services, and unclear and uncertain land tenure systems. It is not any one of the factors but rather the interactions among them that makes these systems and peoples vulnerable.

The global factors leading to increased vulnerability in this region stem from the socioeconomic adjustments to globalization and resource use adjustments resulting from climate warming. In addition, regional adjustments have triggered demographic changes and, in some cases, growth to take advantage of opportunities associated with globalization of the resource base.

The consequences of the latest changes include cropland abandonment, destocking of certain rangelands and increased stocking of others, degradation of soils due to salinization and desertification, and damage to wetlands due to modifications of water regimes and industrial development. A major shift in livestock rates has been observed in the Eurasian steppe, with increases in China and Mongolia, where opportunities arose with free market access, whereas in Central Asian countries major destocking occurred due to loss of social infrastructure. During spring 2003, the region was the source of large dust plumes that traveled as far the North American continent and led to health concerns for the Asian populations in their path.

tains some sort of advantage, such as between remoras and sharks; mutualism refers to a relationship in which both organisms benefit; ammensalism is an interaction in which one organism is harmed and the other is unaffected.) Commensalism is related to facilitation processes like nurse effects and mutualism. For example, the native *Turdus* bird disperses seeds of introduced *Ligustrum lucidum* in Argentina (Marco et al. 2002). An example of mutualism is the introduction of exotic N-fixing bacteria or mycorrhizal fungi with crops (Read et al. 1992).

In many cases, disruption of an interaction in the native habitat, like the absence of pathogens, plays an important role in contributing to the invasive success of exotic plant and animal species. On average, 84% fewer fungi and 24% fewer viruses infect plant species in the naturalized range than in the native range (Mitchell and Power 2003). Torchin et al. (2003) show that invasive animal species lose a significant proportion of the parasite diversity they support in their native habitat. In a survey of 24 invasive animal species, Torchin et al. (2003) show that whereas these species had an average of 16 species of parasites in their native range, only two of the parasites successfully colonized with the host in the new range. The original parasites were supplemented by four parasites native to the host's exotic habitat. This considerable reduction in parasite burden might give introduced species an advantage over native species with a larger diversity of parasites. Invasive plant species that are more completely released from pathogens are more widely reported as harmful invaders of both agricultural and natural ecosystems.

The threats that biological invasions pose to biodiversity and to ecosystem-level processes translate directly into economic consequences such as losses in crops, fisheries, forestry, and grazing capacity (Mack et al. 2000). Mismanagement of semiarid grasslands combined with climatic changes has caused woody plant invasion by native bushes and the loss of grazing lands in North and South America (van Auken 2000). Pimentel (2002) estimated that exotic weeds in crops cost U.S. agriculture $27 billion a year. Marine and estuarine waters in North America are heavily invaded, mainly by crustaceans and mollusks in a pattern corresponding to trade routes (Ruiz et al. 2000). U.S. lakes and watersheds are invaded as well. The costs associated with zebra mussel (*Dreissena polymorpha*) invasion were estimated at $100 million a year by Pimentel et al. (1999), although the $5 billion a year estimated by the Department of Environmental Quality of Michigan Government is perhaps a more realistic figure (Michigan Department of Environmental Quality 2004). Leung et al. (2002) found an expenditure of up to $324,000 per year to prevent invasion by zebra mussels into a single lake with a power plant.

In spite of these alarming figures, can introductions of alien species be beneficial? Some 98% of the U.S. food supply comes from introduced species, such as corn, wheat, rice, and other crops, as well as cattle, poultry, and other livestock (Pimentel 2002). The same proportion of introduced to native food species is likely to be found in most countries. Some species are introduced to control other introduced species, sometimes successfully (*Galerucella calmariensis* and *G. pusilla* to control purple loosestrife in North

America) and sometimes unsuccessfully (*Bufo marinus* (cane toad) to control greyback cane beetle (*Dermolepida albohirtum* (Waterhouse)) and French's Cane Beetle (*Lepidiota frenchi* (Blackburn)) in Australia and other sugar-growing countries).

Many introduced species are alternative resources for native species (for example, alien plants and fruit-eating birds already mentioned). But how many of them have become invasive? In Britain, 71 out of 75 non-native crop plant species are naturalized, in part because they are strongly selected to growth where they are cultivated (Williamson and Fitter 1996). However, not all habitats are equally invasible. In an extensive study of plant invasions in the British Isles, Crawley has shown that lowland disturbed habitats are host to a much larger diversity of alien plant species than are upland habitats, which remain relatively uninvaded (Crawley and May 1987; Crawley 1989).

#### *7.3.4.2 Diseases and Ecosystem Effects*

Many biological invasions are regarded as affecting human well-being, either by affecting public health or by impairing economic activities such as agriculture or fisheries. Among the most common sanitary problems are the invasions by disease-causing organisms or by vectors of disease-causing parasites. Tuberculosis, AIDS, influenza, cholera, bubonic plague, bovine spongiform encephalopathy, and severe acute respiratory syndrome are among the diseases caused by introduced pathogenic biological agents in many countries. For example, more than 100 million people are infected with the influenza virus each year in just the United States, Europe, and Japan. In the United States alone, influenza represents on average $14.6 billion in direct and indirect costs each year. The influenza virus is originally Asiatic, and aquatic birds provide the natural reservoir from which occasional genetic mutations can spread to domestic poultry and humans (Zambon 2001).

While the term "invasive alien species" is commonly associated with plants and insects, parasites and pathogens possess a considerable potential to significantly modify ecosystem function. This potential stems from both their ability to multiply very rapidly and also their diversity. Arguably more than half of biodiversity consists of species that are parasitic on more conspicuous free-living species (Dobson et al. 1992). In the last 20 years, studies demonstrating how pathogens modify and regulate free-living hosts have completely modified our understanding of the role that parasites play in natural and human-modified systems (Dobson and Hudson 1986; Dobson and Crawley 1994; Grenfell and Dobson 1995). Examples from a range of ecosystems and a variety of key processes are reviewed in this section.

Jim Porter and his colleagues have been intensely monitoring the coral communities of the Florida Keys since the early 1990s. The work uses regular digital photographic censuses along fixed transects throughout the Keys, allowing detailed analysis of the growth and structure of the coral community. In the late 1990s the scientists noted dramatic changes in the structure of the coral community at some transects. The dominant structural species, Elkhorn coral, was first infected with a new disease syndrome, white pox disease (the most severely affected Elkhorn species was *Acropora cervicornis*). This infection affected several Elkhorn coral while also rapidly spreading to other coral species (Patterson et al. 2002). Within a few months, once-vibrant coral reefs were reduced to bare rock. The work provides a vivid example of how quickly a pathogen can modify and destroy the structure of a complex community. More disconcertingly, it is but one of an increasing number of examples that suggest pathogen outbreaks are increasing in the oceans (Harvell et al. 1999).

The Florida Keys example echoes a dramatic terrestrial example that occurred almost a century earlier, when rinderpest virus was accidentally introduced into sub-Saharan Africa. Rinderpest virus causes high fatality rates in the hoofed mammals it infects (cattle, wildebeest, and buffalo), is a member of the Morbillivirus family, and is a recent ancestor of human measles. It took 10 years for rinderpest to spread from the Horn of Africa to the Cape. The pandemic it caused reduced the abundance of susceptible species by up to 90% in many areas (Spinage 1962; Plowright 1982).

The huge reduction in the abundance of herbivores had impacts that spread throughout the ecosystems of sub-Saharan Africa (Prins and Weyerhaeuser 1987; McNaughton 1992). Fire frequency increased as uneaten grasses accumulated and ignited during lightning storms in the dry season. This combined with a reduction in browsers to allow miombo bush to spread across areas that were previously grass savannas. The absence of prey caused a decline in the abundance of lions, although other carnivores, such as cheetahs and hunting dogs, may have increased as habitats appeared that were better suited to their hunting methods. More insidiously, the absence of buffalo, wildebeest, and cattle caused tsetse flies to increase their feeding rates on humans, which led to a significant epidemic of sleeping sickness (Simon 1962).

The development of a vaccine for rinderpest in the late 1950s allowed a reversal of many of these trends (Plowright 1982; Dobson and Crawley 1994). Although only cattle have been vaccinated, their role as reservoir hosts is sharply illustrated by the speed at which the pathogen disappeared from wildlife. This in turn led to a reversal of the balance between grassland and miombo bushland and to a significant increase of, first, herbivores and then the carnivores that feed upon them.

In a third example, the fungal disease amphibian chytridiomycosis and other pathogens are implicated in amphibian population declines worldwide (Daszak et al. 2003). Chytridiomycosis appears to be locally increasing in impact or moving into new regions. In common with many emerging infectious diseases of humans, domestic animals, and other wildlife species, the emergence of chytridiomycosis may be driven by anthropogenic introduction. Emerging infectious diseases are linked to anthropogenic environmental changes that foster increased transmission within or between hosts.

These three examples illustrate how the introduction of a novel pathogen has caused ecosystem-wide changes in species abundance. If pathogens were considered as keystone species, they would plainly provide some of the most dramatic examples of individual species that cause dramatic changes in the abundance of all others in the ecosystem (Burdon 1991; Power et al. 1996). As ecologists focus more attention on the role of parasites in natural systems, more examples will be found where highly specific pathogens have significantly affected a single species in a community and caused cascading effects on other species that use the infected species as a resource (Dobson and Hudson 1986; Dobson and Crawley 1994). Nevertheless, this emphasis on dramatic examples of ecosystem change should not distract attention from the fundamental role that endemic parasites play in driving natural processes.

## 7.4 Examples of Interactions among Drivers and Ecosystems

Changes in ecosystem services are almost always caused by multiple, interacting drivers. Changes are driven by combinations of drivers that work over time (such as population and income growth interacting with technological advances that lead to climate change), over level of organization (such as local zoning laws versus international environmental treaties), and that happen intermittently (such as droughts, wars, and economic crises).

Changes in ecosystem services feed back to the drivers of changes. For example, they create new opportunities and constraints on land use, induce institutional changes in response to perceived and anticipated resource degradation, and give rise to social effects such as changes in income inequality (as there are winners and losers in environmental change). Reviews of case studies of deforestation and desertification (Geist and Lambin 2002, 2004) reveal that the most common type of interaction is synergetic factor combinations—combined effects of multiple drivers that are amplified by reciprocal action and feedbacks.

Drivers interact across spatial, temporal, and organizational scales. Global trends like climate change or globalization can influence regional contexts of local ecosystem management. Research on the combined effects of these two major global trends on the local farmers, other agents, and finally on ecosystems is sparse but growing. For example, a study in South Africa found that changes in export prices of cash crops can trigger land use changes on the local level and that removal of national credits and subsidies can make some farmers more vulnerable to environmental changes while others profit from easier access to markets and are less vulnerable to climate change (Leichenko and O'Brien 2002).

Any specific ecosystem change is driven by a network of interactions among individual drivers. Though some of the elements of these networks are global, the actual set of interactions that brings about an ecosystem change is more or less specific to a particular place. For example, a link between increasing producer prices and the extension of production can be found in many places throughout the world. The strength of this effect, however, is determined by a range of location-specific factors including production conditions, the availability of resources and knowledge, and the economic situation of the farmer (Jones 2002). No single conceptual framework exists that captures the broad range of case study evidence (Lambin et al. 2001).

To generalize, simplifications are needed, but these simplifications are often sufficient to explain general trends in ecosystem change. There exists a broad range of scientific schools of generalizing simplifications, each one entering the arena from a different perspective and thus adding different pieces to the broadening knowledge base on causes for ecosystem change. Many of these approaches emerge from disciplinary perspectives, such as spatial (agro-)economic models of land use change (Alcamo et al. 1998; Nelson and Geoghegan 2002). Others use generalizing schemes on a highly aggregated basis like the IPAT approach, where environmental impact is seen as the product of population, affluence, and technology (Ehrlich and Holden 1971; Ehrlich and Daily 1993; Waggoner and Asubel 2002). Others analyze case studies in order to identify common threads and processes (Scherr 1997; Geist and Lambin 2002), sometimes attempting to identify trajectories of environmental criticality (Kasperson et al. 1995) or to formulate qualitative models (Petschel-Held et al. 1999; Petschel-Held and Matthias 2001).

Based on the findings of the Multiscale Assessments of the MA and recent literature, examples of causal complexes for ecosystem change can be given. This section reflects on some of these patterns, organized along major direct drivers.

### 7.4.1 Land Use Change

Ten years of research within the international program on land use and land cover change of IGPB concluded that neither population nor poverty alone constituted the sole and major underlying causes of land cover change worldwide. (See Figure 7.22 in Appendix A.) Rather, responses to economic opportunities, mediated by institutional factors, drive land cover changes. Opportunities and constraints for new land uses are created by local as well as national markets and policies. Global forces become the main determinants of land use change, as they amplify or attenuate local factors (Lambin et al. 2001).

#### *7.4.1.1 Tropical Deforestation*

Case study reviews (Geist and Lambin 2002) as well as findings within the MA's alternatives to slash-and-burn crosscutting Sub-global Assessment reveal regional patterns for tropical deforestation. In all regions of the humid tropics—Latin America, Southeast Asia, and Central Africa—deforestation is primarily the result of a combination of commercial wood extraction, permanent cultivation, livestock development, and the extension of overland transport infrastructure.

However, many regional variations on this general pattern are found. Deforestation driven by swidden agriculture is more widespread in upland and foothill zones of Southeast Asia than in other regions. Road construction by the state followed by colonizing migrant settlers, who in turn practice slash-and-burn agriculture, is most frequent in lowland areas of Latin America, especially in the Amazon Basin.

Pasture creation for cattle ranching is causing deforestation almost exclusively in the humid lowland regions of mainland South America. The spontaneous expansion of smallholder agriculture and fuelwood extraction for domestic uses are important causes of deforestation in Africa. These regional differences mostly come from varying mixes of economic, institutional, technological, cultural, and demographic factors underlying the direct causes of deforestation.

#### *7.4.1.2 Agricultural Intensification*

Agricultural intensification is usually defined as substantial use of purchased inputs, especially fertilizer, in combination with new plant varieties that respond well to the increased inputs. Globally, intensification has been a major contributor to the doubling of food production over the last 40 years (MA *Current State and Trends,* Chapter 8). In higher-income countries, this increase was primarily achieved via intensification. In lower-income countries, 71% of the increase in crop production came from yield growth; the remaining 29% from area expansion (Bruinsma 2003). These successes are tempered by concerns about whether they can be maintained in current locations and about the consequences of the driving forces in regions where intensification has not yet occurred.

Lambin et al. (2001) identify three major pathways toward agricultural intensification that are supported by a number of sub-global assessments:

- Land scarcity in economies weakly integrated into the world markets can be caused by interactions among population growth and institutional changes, such as implementation of legal property rights (Ostrom et al. 1999). For example, the Western Ghat sub-global assessment reports about land reform acts in this respect, by growth in population and its density, where it is often related to land division (Kates and Haarmann 1992). In some instances land scarcity can contribute to deforestation (see the MA sub-global assessments on the Darjeeling Region in India and on Papua New Guinea).
- Market integration (called commodification by Lambin et al. 2001) is brought about by interactions among general infrastructure development (such as road building projects and creation of a national food safety inspection service), changes in macroeconomic policies, and technological change. For an individual farmer, it can mean changes in input prices and availability and changes in sales opportunities and prices. Economic specialization, wage labor, contract farming, and other adjustments follow.
- Region-specific interventions, in the form of state-, donor-, or NGO-sponsored projects, are done to foster development through commercial agriculture. Many of these projects are planned and managed from afar, creating the potential for inefficient management and inadequate attention to specific local constraints. These projects are also vulnerable to changes in government or donor policy and to public-sector financial constraints (Altieri 1999). The Sinai sub-global assessment (Egypt) demonstrates this possibility. Agricultural development projects are designed to attract as many as 6 million people to the Sinai region in order to relieve population pressure from the Nile valley.

#### *7.4.1.3 Urban Growth and Urbanization*

Though only about 2% of Earth's land surface is covered by built-up area (Grübler 1994), the effect of urban systems on ecosystems extends well beyond urban boundaries. Three processes of urban change appear to be of relevance for ecosystem change: the growth of urban population (urbanization), the growth of built-up area (urban growth), and the spreading of urban functions into the urban hinterland connected with a decrease in the urban-rural gradient in population density, land prices, and so on (urban sprawl). Each of these processes has its own pathways in which it affects ecosystems and human well-being:

- Urbanization: In developing countries, urban administration often is not capable of developing needed infrastructure as fast as urban populations grow (Kropp et al. 2001). Insufficient housing conditions, a lack of access to safe water and sanitation, and major health effects follow. Rural-urban migration is an important source of urbanization in developing countries. This arises when opportunities for gainful employment in agriculture cannot keep up with growth in the rural workforce and when urban areas provide the potential of gainful employment. Degradation of rural environments can contribute to the pressure. There is, however, also a reverse effect, with remittances possibly allowing the use of cultural practices that reduce pressure on rural ecosystems.
- Urban growth and sprawl: In industrial countries, urban growth and in particular urban sprawl play a much more significant role: landscapes become fragmented, traffic and energy use increase, and land sealing can change flood regimes. The latter has been observed in the sub-global assessment of the Kristianstad Vattenrike in Sweden as a major driving process of ecosystem change.

### 7.4.2 Tourism

Several of the sub-global assessments report the importance of tourism, both as a driver of ecosystem change and as a potential response option for income generation and reduction of pressure on ecosystems (e.g., the Southern African, Portugal, Caribbean, Trinidad Northern Range, and Costa Rica assessments).

The Southern African Sub-global Assessment provides a good example of how biodiversity serves as an important basis for income generation, thus representing a major asset of a region or community (Biggs et al. 2004). In many areas in Southern Africa, nature-based tourism represents a major source of income, contributing about 9% of GDP in the Southern Africa Development Community region. Though no quantitative estimates on faunal biodiversity exist for the region, it is evident that animal biodiversity is one of the most important motives for tourists. Also, nature-based tourism, together with hunting, contributes to the privatization of the nature conservation efforts in the region, as in private nature parks. This privatization represents an important pillar in the overall conservation efforts in the region.

From an integrated point of view—that is, by considering the region as a whole—tourism appears to be more a driver for ecosystem conservation than for change.

In contrast, the Caribbean Sea Sub-global Assessment shows the other side of tourism—its negative effects on ecosystems and finally on human well-being. Tourism is seen as an indirect and endogenous driver, which together with exogenous drivers acts synergistically on coastal and marine ecosystems in the region. One major exogenous driver in the Caribbean is climate change, with a potential increase in intensity and frequency of tropical cyclones. The evidence of effects of climate change in the recent past is mixed, but it is widely seen as a threat for the future. Other exogenous drivers described by the sub-global assessment include increased river discharge of the Amazon and the introduction of alien bacterial species carried by dust blown from the Sahara. Both bring about changes to marine and coastal ecosystems.

The exogenous drivers in the Caribbean are believed to lower the resilience of the coastal ecosystem to perturbations from infrastructure development along the coast for tourism. These interactions are especially important, as tourism constitutes the single most important income source for many of the Caribbean states (98% of GDP in Barbados, for instance). This decrease in resilience increases the likelihood of major damage by tropical storms, with a direct impact on human well-being.

## 7.5 Concluding Remarks

This chapter has presented an overview of the important drivers of ecosystem change at the global level, with occasional forays into regional effects. It has also sketched out a few of the important links between direct and indirect drivers and the consequences for ecosystems. Readers interested in how these interactions might play out in the future are advised to proceed to later chapters in this volume. Readers interested in more details about how drivers affect individual ecosystems or services should turn to the *Current State and Trends* volume and its chapters on ecosystems and services. Finally, for a review of the plethora of options for human response to undesirable changes, readers are directed to the *Policy Responses* volume.

### Notes

1. This section borrows heavily from Nakićenović 2000, Section 3.3.2.
2. This section borrows heavily from Nakićenović 2000.
3. This section borrows heavily from Convention on Biological Diversity 2003.
4. This section borrows extensively from Nakićenović 2000.

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