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Anthropogenic Drivers of Ecosystem Change: an Overview

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ABSTRACT. This paper provides an overview of what the Millennium Ecosystem Assessment (MA) calls “indirect and direct drivers” of change in ecosystem services at a global level. 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. Global driving forces are categorized as demographic, economic, sociopolitical, cultural and religious, scientific and technological, and physical and biological. Drivers in all categories other than physical and biological are considered indirect. Important direct drivers include changes in climate, plant nutrient use, land conversion, and diseases and invasive species. This paper does not discuss natural drivers such as climate variability, extreme weather events, or volcanic eruptions.

Key Words: *ecosystem services; drivers of change; direct drivers; indirect drivers; demographic drivers; economic drivers; sociopolitical drivers; cultural and religious drivers; scientific and technological drivers; physical and biological drivers; climate change; plant nutrient use; land conversion; diseases; invasive species*

INTRODUCTION

This paper provides an overview of what the Millennium Ecosystem Assessment (MA) calls “indirect and direct drivers” of change in ecosystem services (for more information about the genesis and details of the MA conceptual framework, see Fig. 1 in Carpenter et al. 2006 and Chapter 2 in Millennium Ecosystem Assessment 2003). The underpinning assumption is that ecosystem change is brought about by a complex web of interactions between humans and their surroundings as humans seek to satisfy their basic needs and improve their well-being. To systematize our approach to understanding these interactions, we describe the relationship in terms of “drivers” of ecosystem change. In this paper we provide a heavily condensed summary of the important drivers of ecosystem condition at a global level (for full details, please see Chapter 9 of Millennium Ecosystem Assessment 2005b).

The MA definition of a driver is any natural or human-induced factor that directly or indirectly causes a change in an ecosystem (Carpenter et al. 2006). 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 are demographic, economic, sociopolitical, cultural and religious, scientific and technological, and physical and biological. Drivers in all categories other than physical and biological are considered indirect. Important direct, i.e., physical and biological, drivers include changes in climate, plant nutrient use, land conversion, and diseases and invasive species.

Changes in ecosystem services are almost always caused by multiple interacting drivers. These drivers can work over time, e.g., population and income growth interacting with technological advances that lead to climate change, or over levels

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of organization, e.g., from local zoning laws to international environmental treaties; they can also happen intermittently, e.g., droughts, wars, and economic crises. For example, reviews of case studies of deforestation and desertification (Geist and Lambin 2002, 2004) reveal that synergetic factor combinations are the most common, i.e., the combined effects of multiple drivers that are amplified by reciprocal action and feedbacks.

Drivers interact across spatial, temporal, and organizational scales. Global trends such as climate change or globalization can influence regional contexts of local ecosystem management. For example, a study in South Africa found that changes in the export prices of cash crops can trigger land-use changes at the local level. The removal of national credits and subsidies causes some farmers to become more vulnerable to environmental changes, whereas others profit from easier access to markets and become less vulnerable to climate change (Leichenko and O'Brien 2002).

Any specific ecosystem change is the result of a myriad of interactions among drivers. Although some drivers 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 production growth can be found in many places throughout the world. The strength of this effect, however, is determined by a range of location-specific factors that include 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).

Changes in ecosystem services feed back to the drivers of change. For example, altered ecosystems create new opportunities and constraints on land use, induce institutional changes in response to perceived and anticipated resource degradation and shortages, and give rise to social effects such as changes in income inequality because there are winners and losers in environmental change.

It is important to emphasize at the outset what this paper does not do. First, we do not discuss natural drivers such as climate variability, extreme weather events, or volcanic eruptions. This paper focuses on anthropogenic drivers. Second, we do not discuss interactions among drivers in any detail. Finally, we

do not address the very important issue of how changes in drivers actually affect ecosystems. This paper limits its attention to the drivers themselves.

INDIRECT DRIVERS

We begin with a discussion of the categories of indirect drivers: demographic, economic, sociopolitical, cultural and religious, and scientific and technological.

Demographic drivers

In this section, we address population dynamics by focusing on current conditions and the primary determinants of population change: fertility, mortality, and migration.

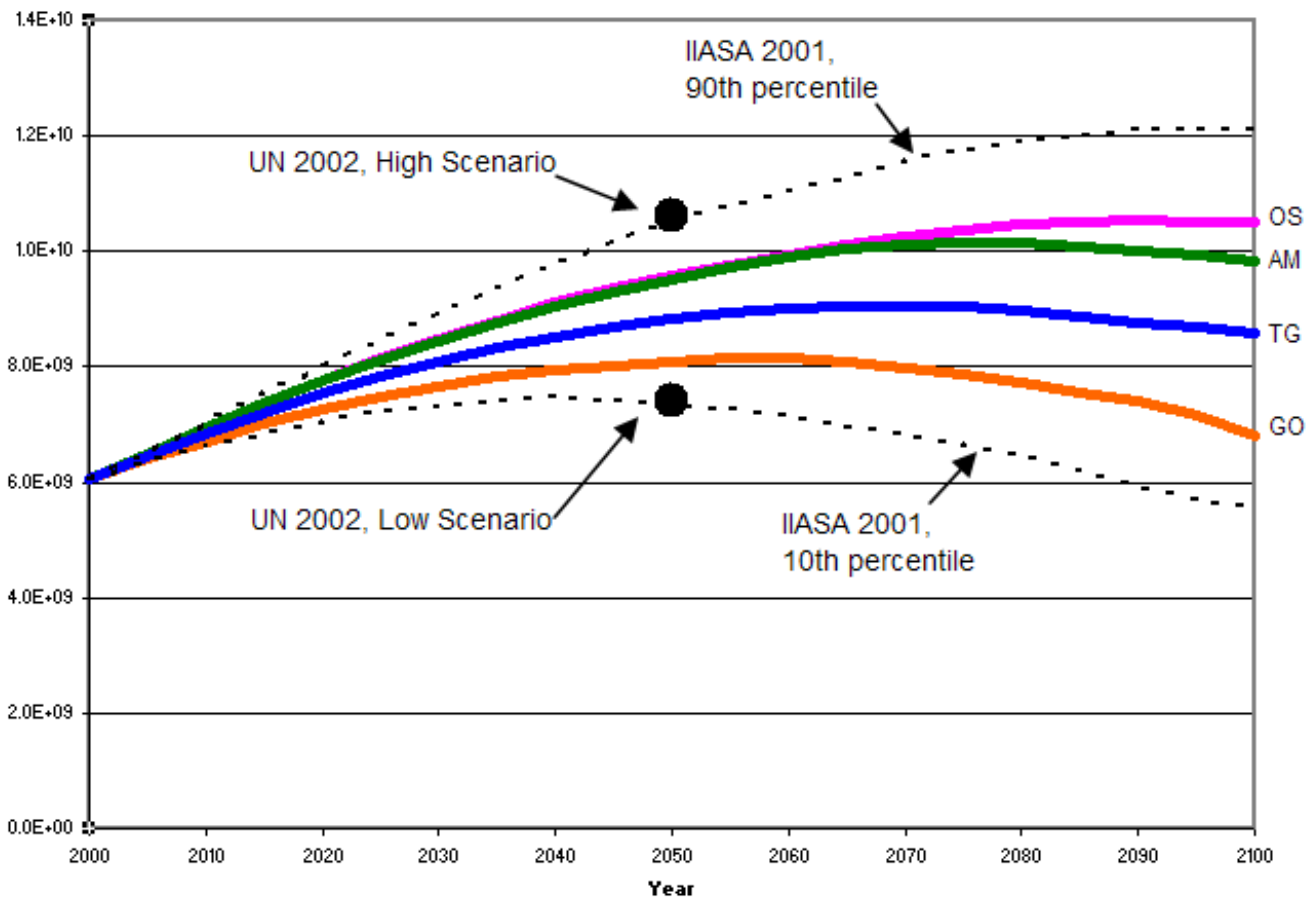
Current conditions

The global population increased by 2×10^9 during the last quarter of the 20th century, reaching 6×10^9 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. At the beginning of the 21st century, population growth rates were declining nearly everywhere. The global growth rate peaked at 2.1%/yr in the late 1960s and has since fallen to 1.35%. Despite the declining growth rate, the global population is likely to increase by another 3×10^9 by 2050 (see Fig. 1). Nonetheless, the end of world population growth, while not imminent, is now on the horizon (Lutz et al. 2001).

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

Traditional demographic country groupings are breaking down. In the USA, 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 the low fertility rates that until recently were found only in high-income countries. Mortality rates vary widely across countries as well. Life expectancies

Fig. 1. Millennium Ecosystem Assessment (MA) world population scenarios. Each curve corresponds to one of the four MA scenarios: Order from Strength (OS), Adaptive Mosaic (AM), TechnoGarden (TG), and Global Orchestration (GO). The International Institute of Applied Systems Analysis (IIASA) data are from Lutz and Goujon (2001). The UN data are from UN (2002). From "Ecosystems and Human Well-being: Scenarios, Volume 2" by Steve R. Carpenter, et al., eds. Copyright (c) 2005 Millennium Ecosystem Assessment. Reproduced by permission of Island Press, Washington, D.C.



are substantially higher in high-income countries (about 75 yr) than in developing countries (63 yr), although the gap has closed from more than 17 yr in the early 1970s to about 12 yr 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, whereas improvements stalled in Russia and have reversed in parts of Africa, mainly because of the impact of HIV/AIDS and wars.

Certain regions are also distinguished by their degree of urbanization. High-income countries typically have populations that are 70–80% urban. Some developing regions, such as parts of Asia, are still largely rural, whereas Latin America, at 75% urban, is indistinguishable from high-income countries in this regard.

The diversity of current conditions means that future demographic change will be highly variable as well. Current age structures are a key determinant of

population growth over the next few decades, because of the “momentum” inherent in young populations. Thus, current high-fertility regions with young age structures (sub-Saharan Africa, the Middle East, and South Asia) have population growth built in, whereas the low fertility and aging populations of most European countries have given them a “negative momentum” that will result in a population decline even if fertility rises in the future (Lutz et al. 2003).

Population growth over the next several decades is expected to be concentrated in low-income urban communities in some developing countries. However, in a few important developing countries, with China as the most dramatic example, population growth will cease because of sharp declines in fertility, and rapid aging of the population is projected.

The demographic transition and determinants of fertility, mortality, and migration

To understand the recent dramatic changes in demographic variables, demographers use the cohort component method, which analyses the determinants of fertility, mortality, and migration and projects trends in these three components to arrive at estimates of future population change. This section briefly sketches the principal determinants for each component and describes the resulting demographic transition.

The demographic transition. The concept of demographic transition is a generalization of the events observed over the past two centuries in those countries with the highest incomes today. These countries 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, Lee 2003). During this type of transition, population growth initially accelerates because the decline in death rates precedes the decline in birth rates, creating a sudden surplus of births over deaths, and then declines as fertility rates fall. The transition is well advanced in all developing countries except in sub-Saharan Africa, and even there the beginnings of a fertility decline are apparent (Cohen 1998, Garenne 2002).

Determinants of mortality. Mortality decline begins with reductions in deaths from infectious diseases, especially of infants, because of improvements in

public health and hygiene and better nutrition as incomes and food availability rise (Lee 2003). Further reductions in mortality are driven by reductions in the incidence of chronic and degenerative diseases such as heart disease and cancer.

In most developing countries, future reductions in mortality and corresponding improvements in life expectancy will be determined by the efficiency of local health services; reductions in the incidence of key diseases such as malaria, tuberculosis, and HIV/AIDS; and improved living standards and education. The future course of the HIV/AIDS epidemic could substantially affect mortality in many countries, especially in sub-Saharan Africa, where HIV prevalence is high. In Botswana, for example, life expectancy dropped from about 65 yr in the early 1990s to 56 yr in the late 1990s and is expected to decline to less than 40 yr by 2005 (UN 2003b).

Determinants of fertility. The basic model of fertility decline assumes that economic development leads to lower fertility because it increases the net cost of children (Becker 1960, Becker and Barro 1988). Parental preferences shift away from large families toward a smaller number of children requiring greater investments in education and health, whereas higher wages and the participation of more women in the labor force increase the opportunity costs of raising children. A range of other factors can be important as well, including the effects of development on attitudes toward fertility regulation (Easterlin 1969, 1975), women’s childbearing desires and their ability to achieve them, shifts in family structures toward the child-centered nuclear family (Caldwell 1982), and the spread of new ideas, particularly regarding birth control (Cleland and Wilson 1987, Bongaarts and Watkins 1996).

Population-related policies have also played a role in recent fertility decreases in developing countries over the past several decades and are likely to affect future fertility. One estimate concluded that 43% of the fertility decline in developing countries between the early 1960s and late 1980s could be attributed to such programs (Bongaarts 1997).

Determinants of international migration. Current and future international migration is more difficult to identify and project than fertility or mortality trends. Migration flows often reflect short-term changes in economic, social, or political factors that

are difficult to predict. Because 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.

Projecting future demographic trends.

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. However, it provides little guidance about future demographic trends for countries that have already achieved low fertility. Total fertility has been below replacement level in 20 European countries for at least two decades and has fallen below replacement level in the 59 developing countries that account for 45% of the world's population (UN 2003a). In some countries, fertility has remained low, whereas in others such as the USA and Sweden, fertility rose nearly to replacement level again and, in Sweden, then returned again to low levels.

Economic drivers: consumption, production, and globalization

Economic activity is a consequence of humans striving to improve their well-being. The outputs of this activity are determined by natural resource endowments, including ecosystem services (natural capital), the number and skills of humans (labor and human capital), the stock of built resources (manufactured capital), and the nature of human institutions, both formal and informal (social capital). In addition to the intended outputs, economic activity can also have side effects, called externalities, with usually negative consequences for ecosystems.

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. This transformation of consumption

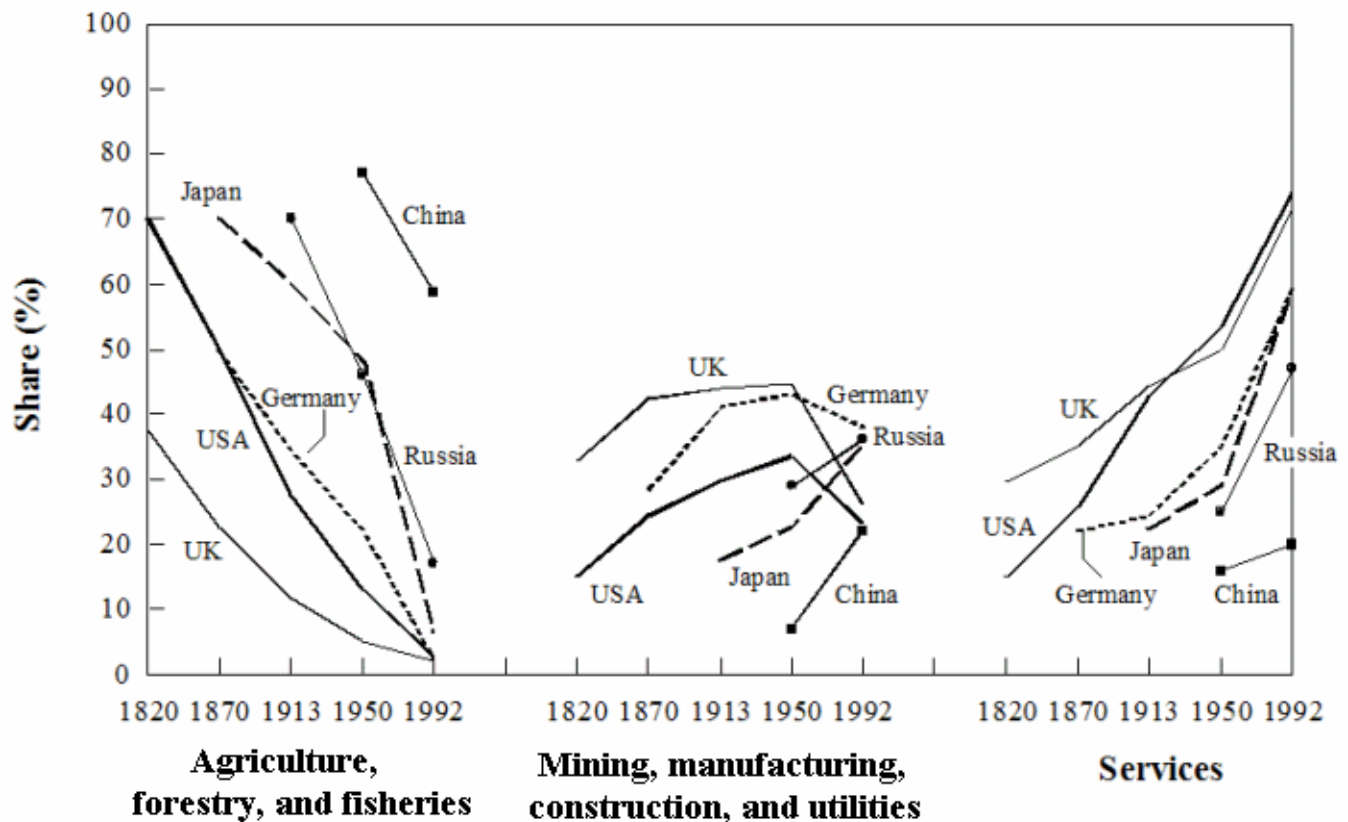
patterns is a consequence of two related facets of human behavior: the limit to the quantity of food one human can consume and the desire for diversity. The first result of this is Engel's law, which is named after the German statistician who first observed the statistical regularity with which, as income grows, the share of additional income spent on food declines. The second is a shift in the primary source of calories from starchy staples, e.g., rice, wheat, root crops, to diverse diets that include more fat, meat, and fish as well as fruits and vegetables as the ability to afford these food groups rises; this phenomenon is known as Bennett's law, after findings in Bennett (1941) and related comparative studies of the consumption of staple foods.

An important consequence of Engel's and Bennett's laws is that, as incomes increase, the demand for nonagricultural goods and services increases faster than demand for agricultural products; this leads to a dramatic change in the structure of economic activity and a true structural transformation. Producers respond by devoting relatively more resources to industry and service activities than to agriculture. The shift to a more diverse and more expensive diet, in particular to more animal- and fish-based protein intake, slows this process, but eventually the demand for more diverse diets is satisfied, and further income growth is spent almost entirely on nonagricultural goods and services.

A consequence of this transformation is that, with income growth, industry's share of output rises initially but then falls, whereas the share of services in economic output rises continuously. In 2000, agriculture accounted for 5% of the world gross domestic product (GDP), industry for 31%, and service industries for 64% (Rosen 2002). Figure 2 documents the shift in economic structure from agricultural production to industry and, to a greater extent, services for the world's largest economies during the past two centuries. In developing regions, the decline in agriculture's share has been especially rapid in recent years, and the growth in services' share has been much faster than was the case historically in the now-rich countries.

The shift away from agriculture to nonagricultural goods and then services is sometimes viewed as a process that ultimately reduces pressures on ecosystems, because services are assumed to be the least demanding of ecosystem products. However, several caveats are in order. First, it is important to distinguish between absolute and relative changes.

Fig. 2. Changes in economic structure for selected countries. The source of the figure is Nakicenovic et al. (2000); the source of the data is Maddison (1995). From "Ecosystems and Human Well-being: Scenarios, Volume 2" by Steve R. Carpenter, et al., eds. Copyright (c) 2005 Millennium Ecosystem Assessment. Reproduced by permission of Island Press, Washington, D.C.



With economic growth, the industrial and service sectors grow more rapidly, so, although the relative contribution of agriculture declines, the high-income countries almost always produce more agricultural output than they did when they were poor. Second, as labor leaves agriculture for the industrial and services sectors, induced technological change substitutes capital for labor in agriculture, potentially altering the composition of the demand for ecosystem services. Finally, urbanization also influences the structure of consumption, increasing the service content dramatically. For example, 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.

A few examples from Asian countries with rapidly rising incomes illustrate these phenomena, although similar changes are now occurring throughout the developing world and have already taken place in the industrial world in the 20th century. In China, 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 occurring in India, with a doubling of calories derived from fat over a 20-yr period. Although Indian consumption of rice and wheat has been increasing, the percentage of all cereals in household expenditures 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, vegetables, and vegetable oils (USDA 2001).

The use of supermarkets is one mechanism by which the output of services in an economy grows, even in agriculture-related activities. By 2002, the share of supermarkets in the retail market for processed and packaged food 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 2004).

Economic growth, distribution, and globalization

Beyond the basic observations that underlie the structural transformation discussed above, the effects of economic activity on ecosystems depend on a number of factors, including the location of that activity, resource endowments and ecosystem condition, available technologies, policies, and market reach. We begin this section with a summary of economic growth statistics and then discuss key determinants.

Perhaps the most comprehensive current compilation of data on historical economic growth is that of Maddison (2003; see Table 1). His data show that, since 1820, the global GDP has increased by a factor of 40, or at a rate of about 2.2%/yr. Between 1950 and 2000, the 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 20th century, income was distributed unevenly both within countries and around the world (see Fig. 3). Although the level of per capita income was highest in North America, Western Europe, Australasia, and Northeast Asia (see Fig. 4), growth rates were highest in South Asia, China, and parts of South America (see Figs. 5 and 6). If these trends continue, global income disparities will be reduced, although within-country disparities might increase. Africa is a conspicuous exception to the trend of growing incomes.

Economic growth is facilitated by trade, which allows countries to exploit the differences in relative abundance of natural and human capital and

differences in tastes across borders. Growth in international trade flows has exceeded growth in global production for many years, and the differential may be growing (Fig. 7). In 2001, international trade in goods was equal to 40% of the gross world product (World Bank 2003). The growth of trade in manufactured goods has been much more rapid than that of trade in agricultural or mining products (Fig. 8).

Determinants of economic growth and development. Economic growth and development depend on the increasing availability and mobility of resources, the efficiency with which they are used, and the institutional and policy environment. For per capita output to increase, total output must grow more rapidly than the population.

Research based on historical evidence allows a number of generalizations as to patterns of advances in productivity and economic growth, including the importance of economic openness to trade and capital flows, the contribution of technological change either through innovation or adoption, and the importance of developing human capital.

There is strong empirical evidence of a positive relationship between trade openness and productivity, industrialization, and economic growth (Barro 1997). 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). 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. Dosi et al. (1990) highlight the critical roles of policies and institutions in realizing economic gains from trade.

International capital flows are critical to economic growth because they relieve resource constraints and often facilitate technology transfers that enhance the productivity of existing resources. The late 20th-century trend toward more open economies led to greater uniformity in macroeconomic monetary, fiscal, and exchange rate policies across the world and made it easier to move capital across national borders. However, 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).

Table 1. Per capita gross domestic product growth rates for selected regions and time periods (percent per year).

Region	1870–1913	1913–1950	1950–1980	1980–1992	1990–2000
Western Europe	1.3	0.9	3.5	1.7	1.7
Australia, Canada, New Zealand, USA	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

Productivity growth, which is essential to improvements in per capita income, requires the development and adoption of new technologies. Expenditures on research and development have high returns, although late-developing countries can, for a time, rely on adapting technologies developed elsewhere to improve productivity. Growth rates tend to be lower for economies at the technology and productivity frontier. For instance, 19th-century productivity and per capita GDP growth rates in the rapidly industrializing USA far exceeded those of England, which by then had reached this frontier. Likewise, in the post-World War II period, growth rates in Japan and most of Western Europe exceeded rates in the USA, which had also reached the frontier (Maddison 1991, 1995). The developing economies of Asia achieved high per capita GDP growth rates beginning in the 1960s (Maddison 1995).

Economic growth requires an expansion of the physical and institutional infrastructure, whose development can have large 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 paper evaluating 132 studies on desertification, infrastructure extension was cited 73 times (Geist and Lambin 2004).

Economic productivity and energy and materials use. Economy activity requires energy and physical inputs, some of which are ecosystem services, to produce goods and services. By-products such as CO₂ and other greenhouse gases, nutrients losses, and the waste stream can cause substantial ecosystem damage. The rate of conversion of inputs to economically valuable outputs is an important determinant of the impact on ecosystems. With more efficient conversion, fewer inputs are needed, and the potential for by-product effects on ecosystems per unit of economic output is reduced.

Materials and energy inputs per unit of economic activity are defined as “materials” and “energy intensity,” respectively. Figure 9 shows material intensity vs. per capita income data for 13 world regions for several metals (van Vuuren et al. 1999). Figure 10 shows a similar curve for total energy intensity for China, India, Japan, and the USA, again as a function of per capita income (Nakicenovic et al. 1998).

Fig. 3. Income level and distribution, 1970 and 2000 (Barro and Sala-i-Martin 2004). The data used are adjusted to 1985 prices and to purchasing power parity and draw on Penn World Tables (see <http://dataentre2.chass.utoronto.ca/pwt/>). From "Ecosystems and Human Well-being: Scenarios, Volume 2" by Steve R. Carpenter, et al., eds. Copyright (c) 2005 Millennium Ecosystem Assessment. Reproduced by permission of Island Press, Washington, D.C.

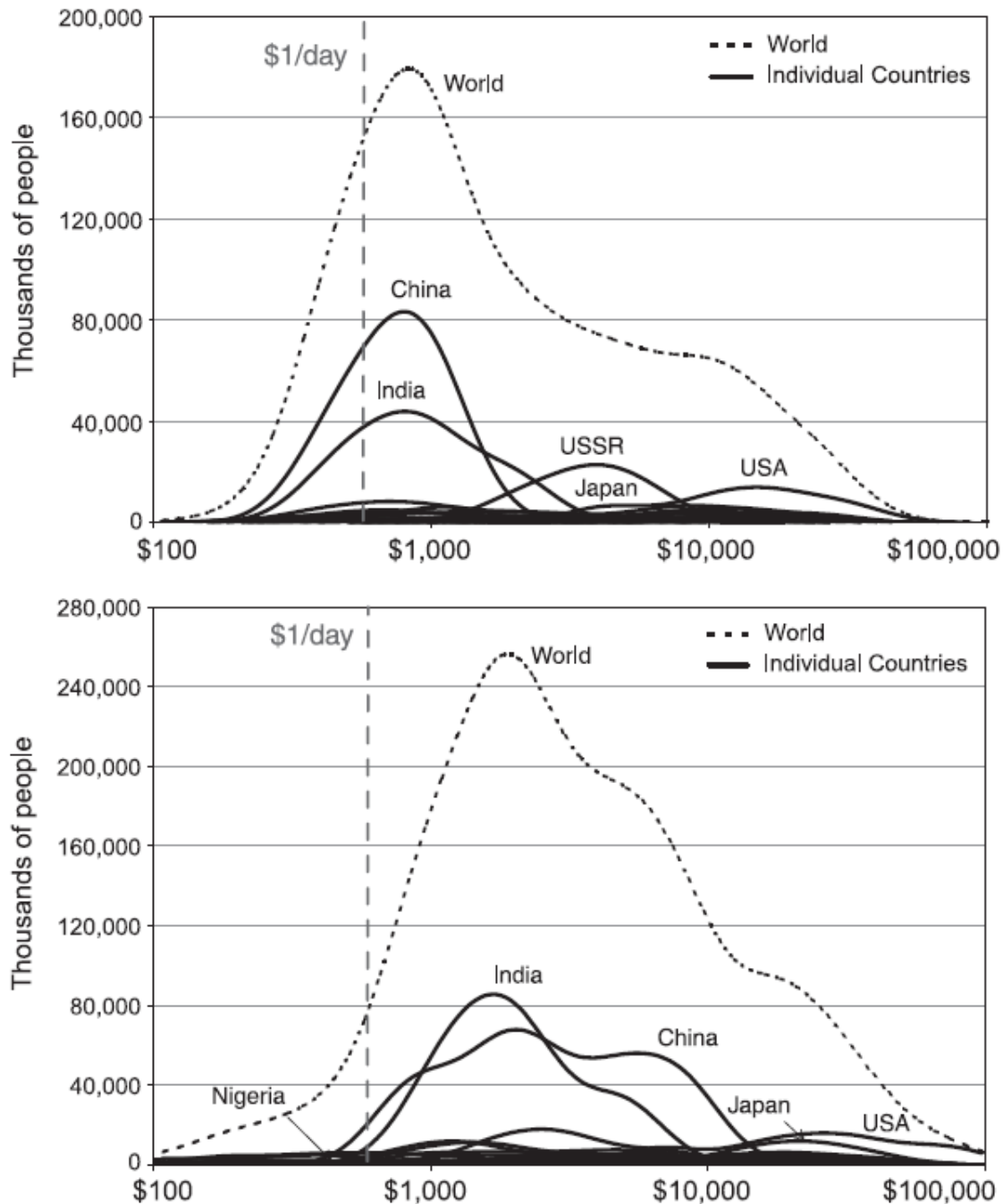
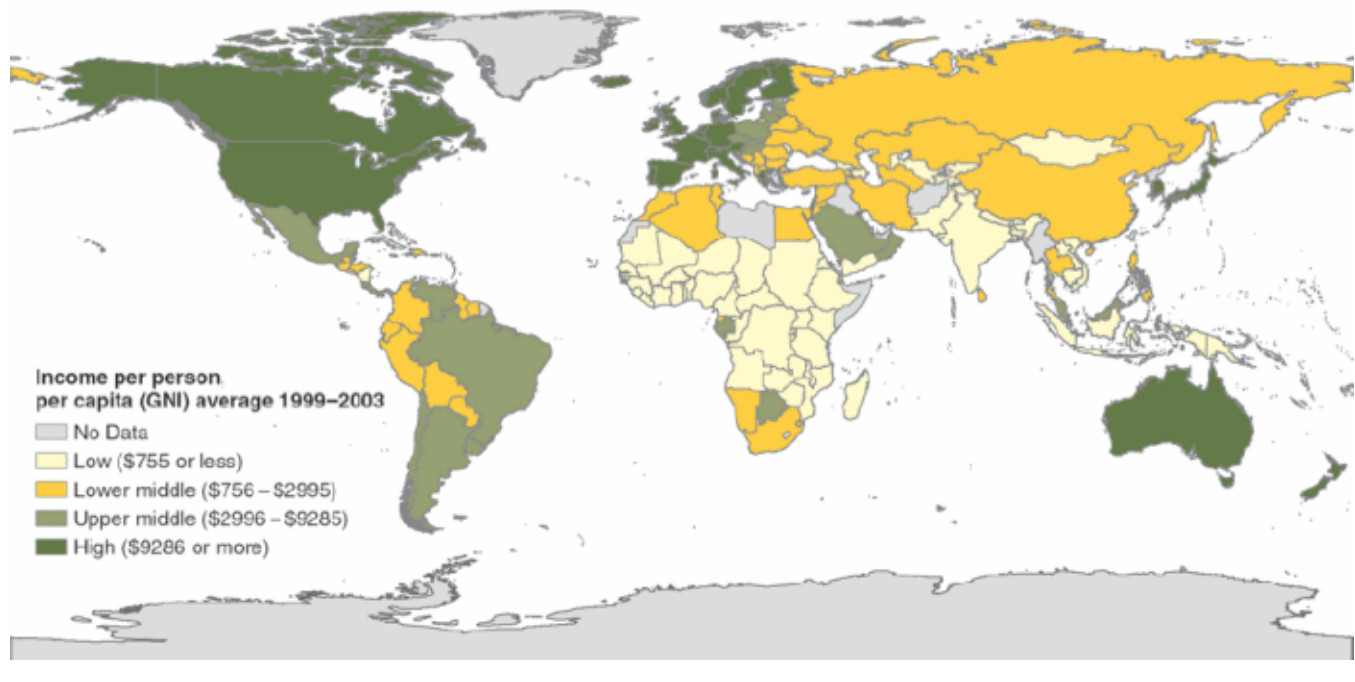


Fig. 4. Gross national income per person averaged for the period 1999–2003. National income is converted to U.S. dollars using the World Bank Atlas method. U.S. dollar values are obtained from domestic currencies using a 3-yr weighted average of the exchange rate (World Bank 2003). From "Ecosystems and Human Well-being: Scenarios, Volume 2" by Steve R. Carpenter, et al., eds. Copyright (c) 2005 Millennium Ecosystem Assessment. Reproduced by permission of Island Press, Washington, D.C.



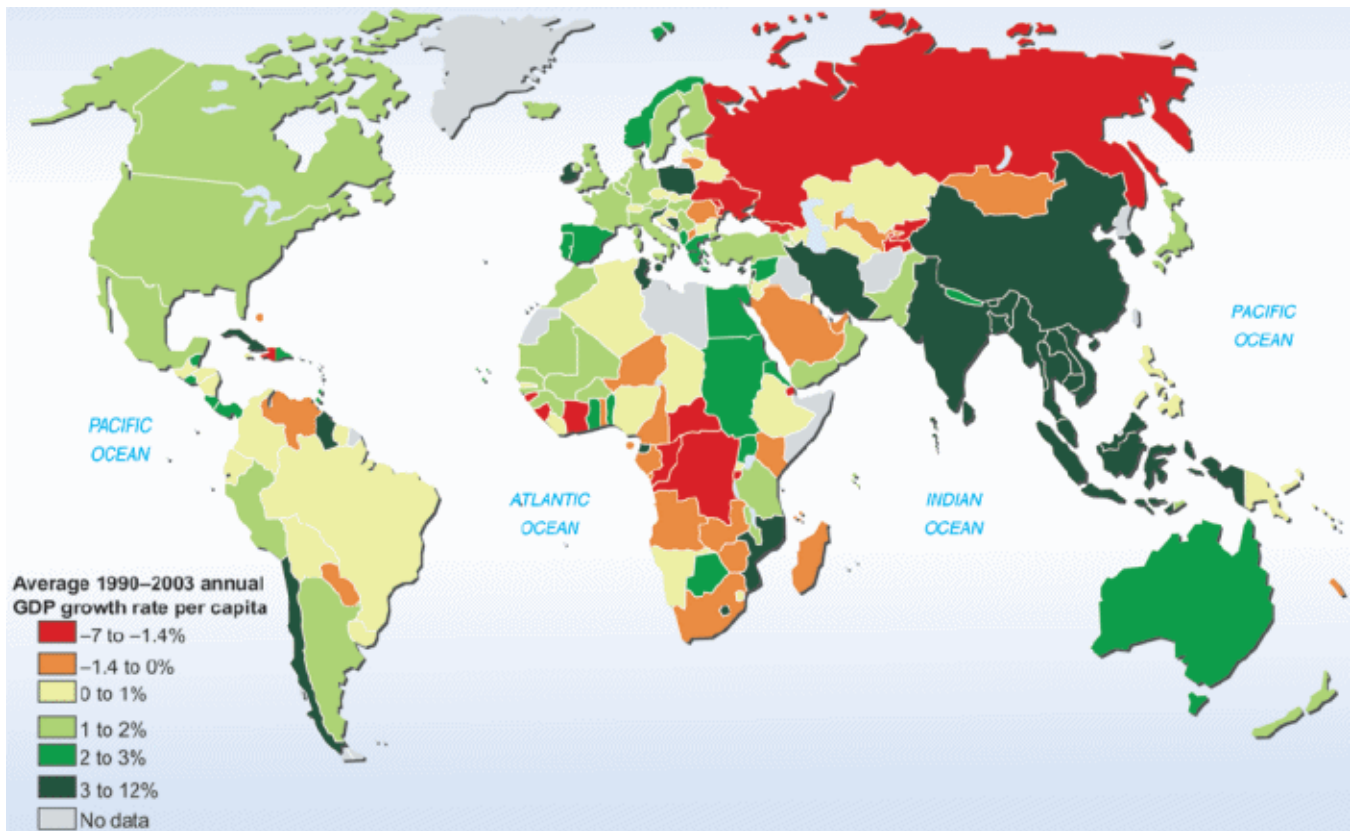
Some evidence suggests that materials and energy intensity follow an inverted U-curve (the IU hypothesis) as income grows; that is, the requirements per unit of economic activity rise for some earlier increases in economic activity and then decline. For some materials, the IU hypothesis (Moll 1989, Tilton 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.

The commercial energy intensity of the GDP generally follows the IU hypothesis as well. The initial rising part of commercial energy intensity stems from replacing traditional energy sources and technologies with modern commercial energy sources. Traditional energy sources such as fuelwood, manure, and crop residues have low energy intensity relative to modern energy sources

such as oil products and electricity. Furthermore, 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). The shift to commercial energy sources is accompanied by the adoption of improved technologies that reduce intensity. Consequently, as seen in Fig. 11, the resulting aggregate total of commercial plus noncommercial energy intensity shows a persistent declining trend (Watson et al. 1996, Nakicenovic et al. 1998).

Two important points emerge from Figs. 9–11. First, energy and materials intensity, i.e., 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.

Fig. 5. Average annual growth rate of gross domestic product per capita, 1990–2003. From "Ecosystems and Human Well-being: Scenarios, Volume 2" by Steve R. Carpenter, et al., eds. Copyright (c) 2005 Millennium Ecosystem Assessment. Reproduced by permission of Island Press, Washington, D.C



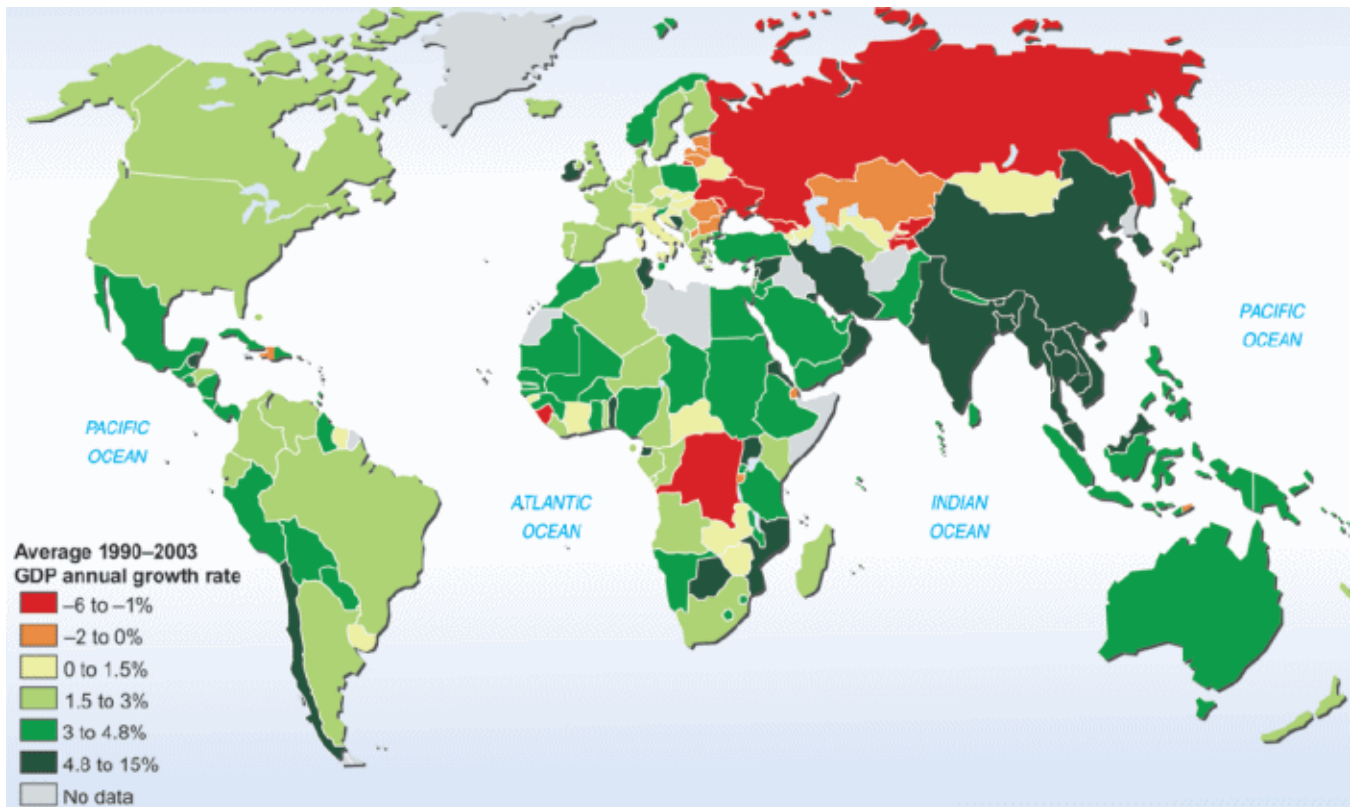
Second, growth in productivity and intensity has historically been outpaced by the growth in economic output. Hence, materials and energy use has risen in absolute terms over time (see, for example, Grübler 1998). An important issue for ecosystems is whether technological advancement can outpace economic growth and lead to reductions in materials and energy use.

Table 2 reports selected macroeconomic, labor, energy, and material productivity increases that have been achieved in a range of economies and sectors at different times. (See also *Scientific and technological drivers*.) Of these examples, productivity increases are the highest for communications. Many observers consider that communication technologies will be as important a driver of economic growth in the future as

traditional resource- and energy-intensive industries have been in the past. Low historical rates of energy intensity improvement reflect the low priority placed on energy efficiency by most producers and users of technology because energy costs have only about a 5% share of the GDP. In contrast, labor has a much larger share of the GDP, and improvements in labor productivity were above 2%/yr over the period 1870–1992.

Government policies can distort market outcomes by increasing or reducing prices and changing production and consumption levels. However, the consequences for ecosystems are neither straightforward nor uniform. By some estimates, distortions in agricultural markets are the largest. Total support to agriculture in OECD countries from market-altering government policies averaged more than

Fig. 6. Average annual growth rate of gross domestic product, 1990–2003. From "Ecosystems and Human Well-being: Scenarios, Volume 2" by Steve R. Carpenter, et al., eds. Copyright (c) 2005 Millennium Ecosystem Assessment. Reproduced by permission of Island Press, Washington, D.C.



$\$324 \times 10^9$ annually in 2001–2003. About three quarters of this amount was used to support farm income directly, whereas the remainder went into general infrastructure improvements, research, marketing, and so on (OECD 2004). Much of the cost was for subsidies in the form of higher prices to farmers, thus providing a 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 much support for research, marketing, and transportation infrastructure (Anderson and Hayami 1986).

Annual global energy subsidies currently total $\$200 \times 10^9$ (de Moor 2002). OECD countries spend some $\$82 \times 10^9$ each year subsidizing energy production, mostly through tax breaks, cheap provision of public infrastructure and services, subsidized capital, and

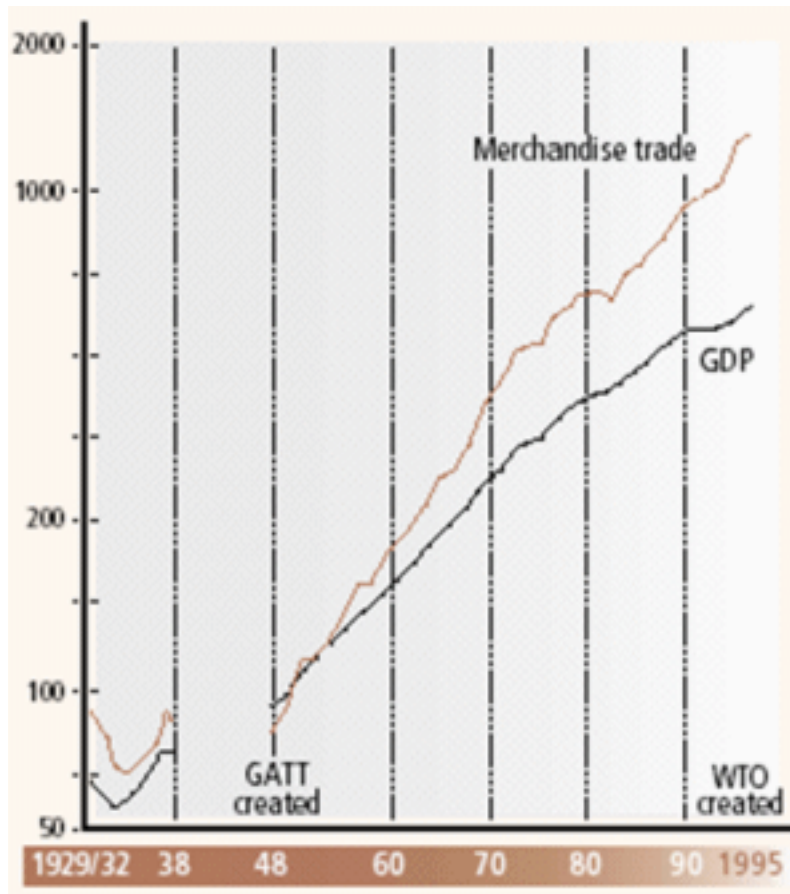
price support (OECD 1997). Globally, more than 80% of these subsidies are for the use of fossil fuels, among the most polluting energy sources.

Sociopolitical drivers

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

Most observers would agree that sociopolitical driving forces have been important in past environmental change (see, for example, de Vries and Goudsblom 2002). However, with some

Fig. 7. Growth of world trade and gross domestic product (GDP), 1930–1995. GATT stands for General Agreement on Tariffs and Trade, and WTO for World Trade Organization. Source: World Trade Organization (2003:13). From "Ecosystems and Human Well-being: Scenarios, Volume 2" by Steve R. Carpenter, et al., eds. Copyright (c) 2005 Millennium Ecosystem Assessment. Reproduced by permission of Island Press, Washington, D.C.



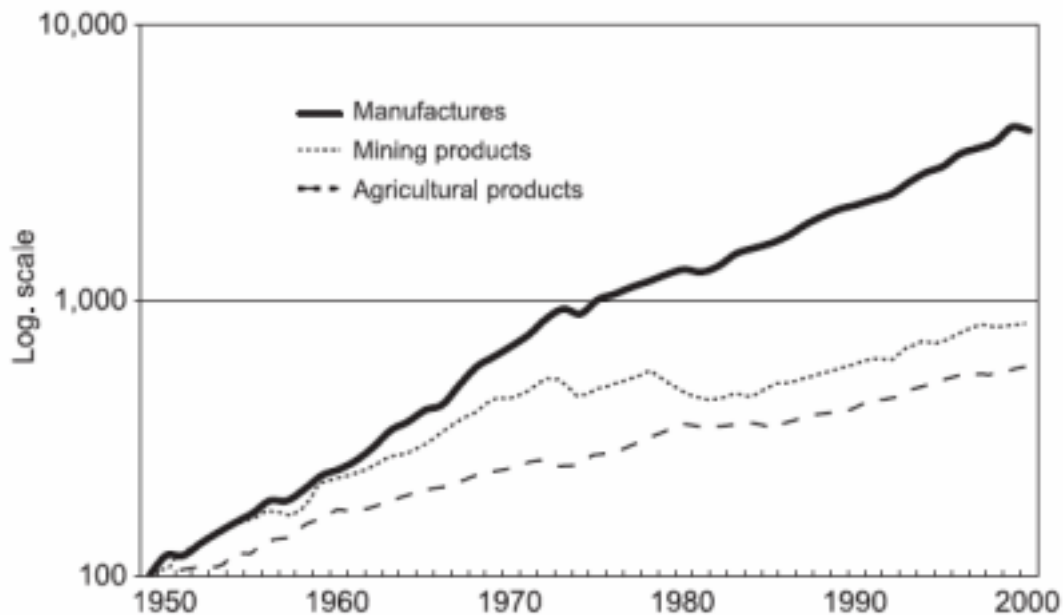
exceptions, such as public participation and governance of the commons, empirical research is limited, as is the basis for strong conclusions about how these drivers work. Sociopolitical drivers may be some of the most fundamental elements of how humans influence the environment. One important element of sociopolitical drivers, i.e., human conflicts, acts both as a direct and an indirect driver of change in ecosystem services and human well-being when nature becomes the recipient of “collateral damage.” 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 (Berhe 2000).

The literature on public participation in environmental assessment and decision making indicates that such involvement at the local and regional levels generally leads to more sustainable approaches to managing resources (Beierle and Cayford 2002, Dietz et al. 2003).

Some strong generalizations have emerged from the literature on the governance of commons (Ostrom et al. 2002) that contrast with Hardin’s original stark

Fig. 8. World merchandise trade by major trade groups 1950–2001 (WTO 2002). From "Ecosystems and Human Well-being: Scenarios, Volume 2" by Steve R. Carpenter, et al., eds. Copyright (c) 2005 Millennium Ecosystem Assessment. Reproduced by permission of Island Press, Washington, D.C.



conclusions about the “tragedy of the commons” (Hardin 1968). We are more likely to govern commons sustainably when:

- resources and the 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;
- outsiders can be excluded at relatively low cost from using the resource; and
- users support effective monitoring and rule enforcement (Dietz et al. 2003:1908).

Cultural and religious drivers

The word “culture” has many definitions in both the social sciences and 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. In this sense, culture conditions the individual’s perceptions of the world, influences what he or she considers important, and suggests courses of action that are appropriate and inappropriate. Although 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.

Broad comparisons of whole cultures have not proved useful because they ignore vast internal variations in values, beliefs, and norms. However, a growing number of studies have been conducted

Fig. 9. Metals intensity with changes in gross domestic product (GDP) per capita expressed as purchasing power parity (PPP) for 13 world regions. Source: Nakicenovic et al. (2003). Metals include refined steel and MedAlloy, which represents the sum of copper, lead, zinc, tin, and nickel. The dashed curves are isolines that represent a constant per capita consumption of metals. The thick line indicates the inverse U-shaped curve that best describes the trends in the different regions as part of a global metal model (Van Vuuren et al. 1999). From "Ecosystems and Human Well-being: Scenarios, Volume 2" by Steve R. Carpenter, et al., eds. Copyright (c) 2005 Millennium Ecosystem Assessment. Reproduced by permission of Island Press, Washington, D.C.

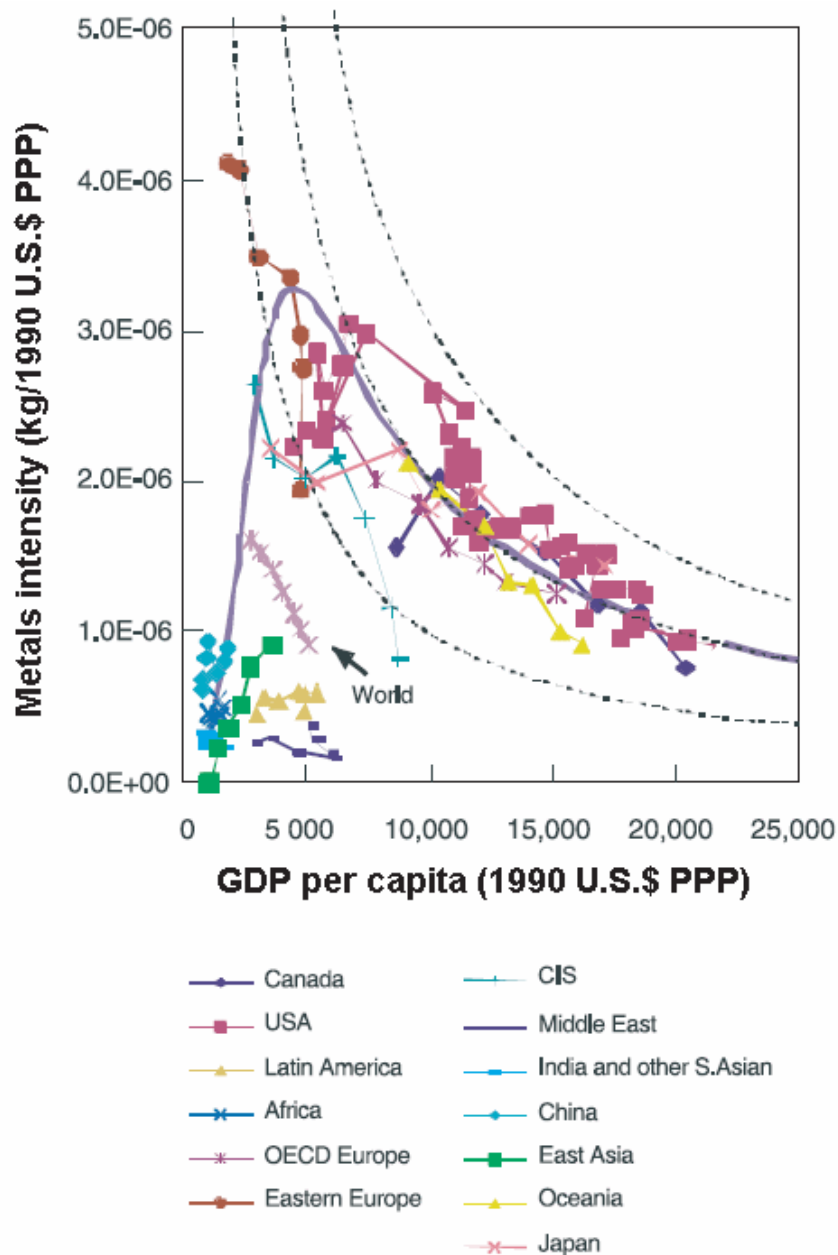
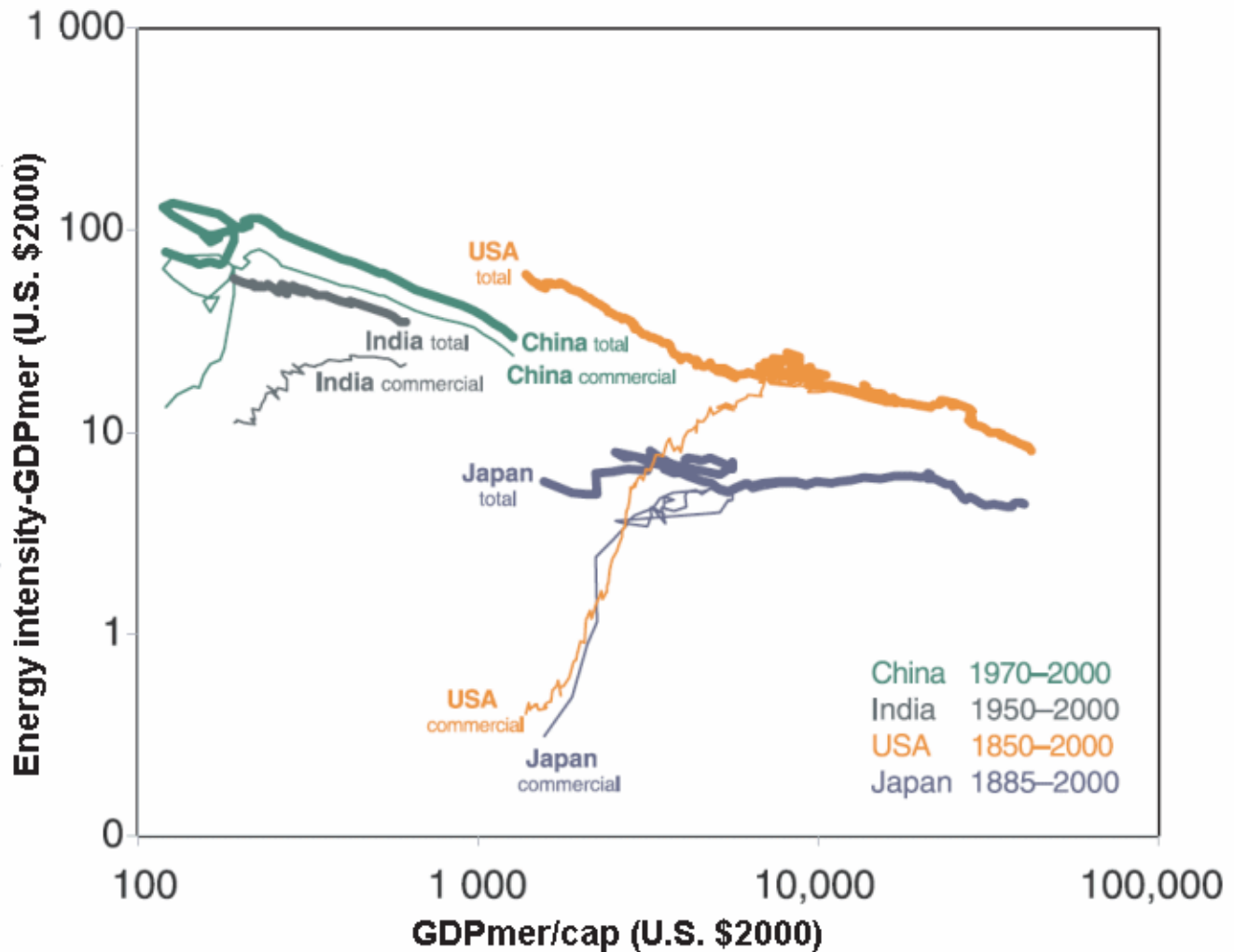


Fig. 10. Energy intensity changes with changes in per capita (cap) income for China, India, Japan, and the USA. Historical data for the USA since 1800 are presented. Data are converted from domestic currencies using market exchange rates (mer). GDP stands for gross domestic product. Source: Nakicenovic et al. (1998). From "Ecosystems and Human Well-being: Scenarios, Volume 2" by Steve R. Carpenter, et al., eds. Copyright (c) 2005 Millennium Ecosystem Assessment. Reproduced by permission of Island Press, Washington, D.C.

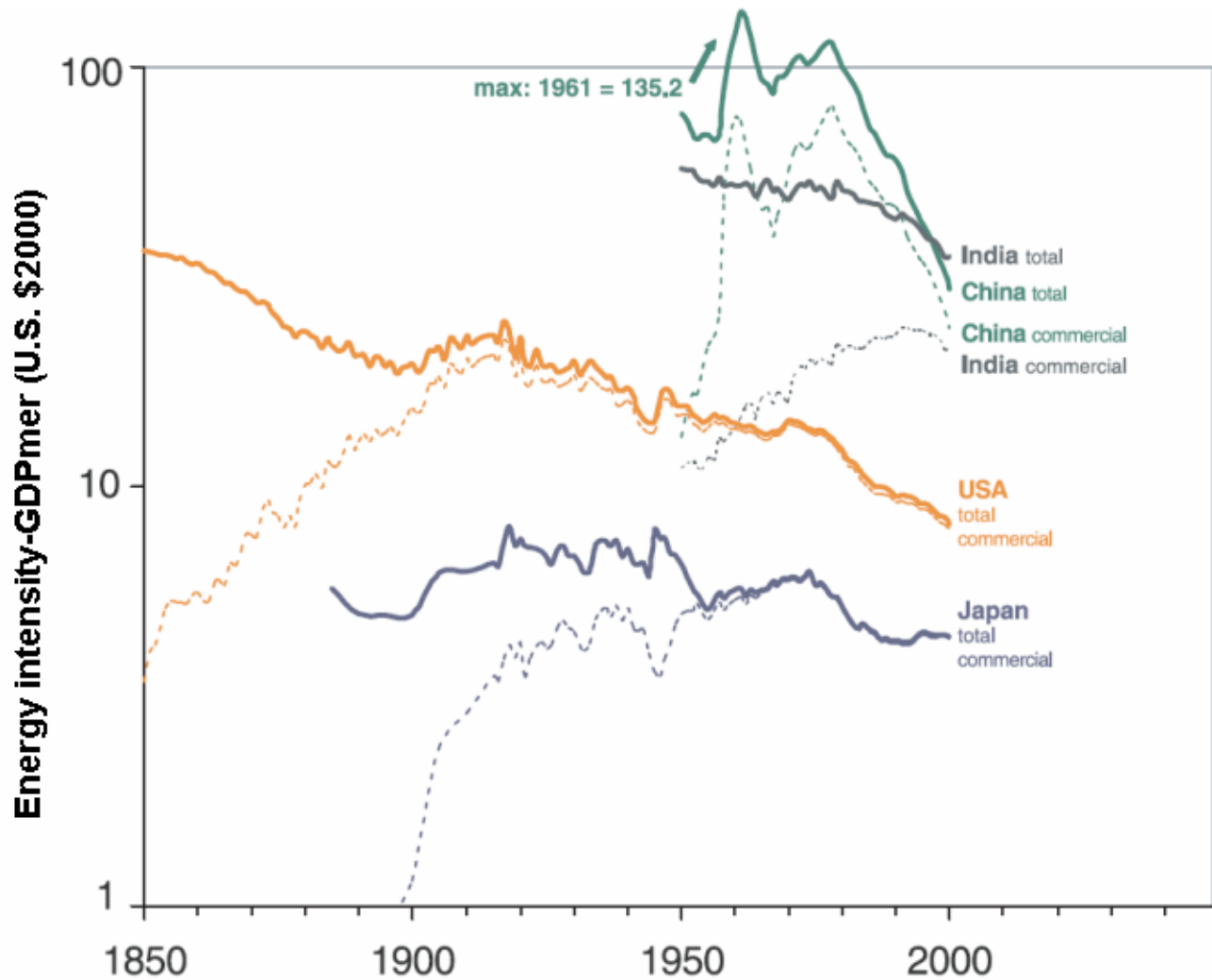


in parallel in multiple societies and allow for systematic examination of the role of culture without overgeneralizing (Dunlap and Mertig 1995, Rosa et al. 2000, Hanada 2003).

It is clear that there is broad concern with the environment across the globe (Dunlap et al. 1993), but it is less clear how that concern translates into either changes in consumer behavior or political

action. 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 the lumber they purchase.

Fig. 11. Energy intensity changes over time for China, India, Japan, and the USA. Data are converted from domestic currencies using market exchange rates. GDP stands for gross domestic product, mer for market exchange rate. Source: Nakicenovic et al. (1998). From "Ecosystems and Human Well-being: Scenarios, Volume 2" by Steve R. Carpenter, et al., eds. Copyright (c) 2005 Millennium Ecosystem Assessment. Reproduced by permission of Island Press, Washington, D.C.



A tradition stretching from Kluckholm (1952) through Rokeach (1968, 1973) to Schwartz (1992) has provided theoretical and empirical arguments to support the idea that values, i.e., the things that people consider important in their lives, are important in shaping behavior and are relatively stable over the life course. Two strains of research have applied this logic to environmental concerns. Inglehart (1995) has suggested that a set of values

he calls "post-materialist" predicts environmental concern. His argument is that only when people have achieved a reasonable degree of material security can they assign priority to issues such as the environment. However, there is considerable controversy regarding the empirical support for this argument at either the individual or the national level (e.g. Stern et al. 1999, York et al. 2003).

Table 2. Examples of productivity growth. GDP stands for gross domestic product.

Sector/Technology	Region	Productivity indicator	Period	Annual productivity change (%)
Whole economy †	12 European countries	GDP/capita	1870–1992	1.7
Whole economy †	12 European countries	GDP/hour worked	1870–1992	2.2
Whole economy †	USA	GDP/hour worked	1870–1973	2.3
Whole economy †	USA	GDP/hour worked	1973–1992	1.1
Whole economy †	Japan	GDP/hour worked	1950–1973	7.7
Whole economy †	South Korea	GDP/hour worked	1950–1992	4.6
Whole economy ‡	World	GDP/primary energy	1971–1995	1.0
Whole economy ‡	OECD	GDP/primary energy	1971–1995	1.3
Whole economy ‡	USA	GDP/primary energy	1800–1995	0.9
Whole economy ‡	UK	GDP/primary energy	1890–1995	0.9
Whole economy ‡	China	GDP/primary energy	1977–1995	4.9
Whole economy §	Japan	GDP/material use	1975–1994	2.0
Whole economy §	USA	GDP/material use	1975–1994	2.5
Agriculture †¶	Ireland	Wheat (t/ha)	1950–1990	5.3
Agriculture †	Japan	Rice (t/ha)	1950–1996	2.2
Agriculture †	India	Rice (t/ha)	1950–1996	2.0
Industry †	OECD (6 countries)	Value added/hour worked	1950–1984	5.3
Industry †	Japan	Value added/hour worked	1950–1973	7.3
Industry ‡	OECD	Industrial production/energy	1971–1995	2.5
Industry ‡	OECD	Industrial production/energy	1974–1986	8.0
New cars #	USA	Vehicle fuel economy	1972–1982	7.0
New cars #	USA	Vehicle fuel economy	1982–1992	0.0
Commercial aviation ††	World	Ton-km/energy	1974–1988	3.8
Commercial aviation ††	World	Ton-km/energy	1988–1995	0.3
Commercial aviation ††	World	Ton-km/labor	1974–1995	5.6

(con'd)

Telephone call costs [†]	Transatlantic	London/NY, cost for 3 min	1925–1995	8.5
Telephone cables [†]	Transatlantic	Telephone calls/unit cable mass	1914–1994	25.0

[†]Data Source: Maddison (1995).

[‡]Data Source: OECD and IEA statistics.

[§]Data Source: World Resources Institute (1997)

^{||}Data Source: FAO (1963–1996) Production Statistics.

[¶]Data Source: OECD (1998), Waggoner (1996), Hayami and Ruttan (1985)

[#]Data Source: Including light trucks, Schipper (1996)

^{††}Data Source: International Civil Aviation Organization (1995)

Scientific and technological drivers

The development and diffusion of scientific knowledge and technologies that exploit knowledge have profound implications for ecological systems and human well-being. The 20th century saw tremendous advances in our understanding how the world works and in the applications of that knowledge to human endeavors. Earlier sections have documented examples of tremendous productivity gains in many industries. We focus here on agricultural science and technology because of its obvious implications for land conversion and widespread consequences for many ecosystems.

The groundbreaking research of Gregor Mendel in the 1860s on the heritability of phenotypical characteristics in garden peas laid the foundation for 20th-century advances in plant and livestock breeding research (Huffman and Evenson 1993). Since the beginning of the 20th century, there have been two waves in the development and diffusion of biological technology in agriculture. The first wave took place mainly in North America and Europe in the 1930s and focused on important temperate-climate crops. The discovery of yield increases from hybrid crop varieties, i.e., those in which two genetically distinct cultivars or inbred lines from different parent plants can produce a plant of greater vigor and higher yield than the parents, and the commercialization of technology that dramatically lowered the price of nitrogenous fertilizers and led to a rapid increase in their use, set the stage for major yield improvements in some of the most important food crops in high-income countries, especially maize. Average U.S. maize

yields improved from 24.4 bushels/acre (1.53 t/ha) in 1860 to 116.2 bushels/acre (7.31 t/ha) in 1989, a more than fourfold increase over about 130 yr. However, even crops such as wheat, for which hybridization has not been commercially viable, saw similar improvements. Wheat yields grew from 11.0 bushels/acre (0.74 t/ha) in 1860 to 32.8 bushels/acre (2.21 t/ha) in 1989 (Huffman and Evenson 1993).

The second wave of agricultural technology development, sometimes called the Green Revolution, 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. Yields of the major cereals, especially with increased use of inorganic fertilizers with high nitrogen contents, have continued to rise at a linear rate after the initial dramatic shifts in the 1960s for rice and wheat. For example, Table 3 shows that yields in irrigated spring wheat have risen at the rate of 1%/yr over the past three decades, an increase of about 100 kg·ha⁻¹·yr⁻¹ (Pingali and Rajaram 1999).

Although high-potential environments gained the most in terms of productivity growth from these modern crop 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

Table 3. Rate of growth of wheat yield by mega-environment, Elite Spring Wheat Yield Trial, 1964–1995.

Period	ME1	ME2	ME4	ME5
1964–1978				
Percent per year	1.22	1.72	1.54	1.41
Kg per year	71.6	81.5	32.4	34.9
1979–1999				
Percent per year	0.82	1.16	3.48	2.10
Kg per year	53.5	62.5	87.7	46.1

and unfavorable environments was one of the primary means of redistributing the gains of technological change. The wages of workers in unfavorable environments are pulled up by the demand for additional labor in the favorable environments. Renkow (1993) found similar results for wheat grown in high- and low-potential environments in Pakistan.

Most of the increase in agricultural output over the past 40 yr has come from an increase in yields per hectare rather than an expansion of the 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% (FAO 2004). Achieving these substantial increases in yields reduced the need to expand the amount of area cropped, which in turn reduced the pressure to convert natural ecosystems to farmland (Waggoner 1996, Tilman et al. 2002). At the same time, the overuse or inappropriate use of inputs has had negative effects on ecosystem services.

A third wave of agricultural technology development based on techniques for transferring genetic material from one organism to another to produce organisms that would not occur via normal reproductive methods is in its early stages. The initial commercialized products of this technology, glyphosate-resistant soybeans and maize and cotton

that are resistant to lepidopteran pests, were developed 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 chemical pest control. Varieties of food crops with other desirable characteristics such as the so-called golden rice with increased beta-carotene content, wheat with increased drought tolerance, and papaya with improved virus resistance are in various stages of development.

Rapid innovation in agriculture in the past century required supporting institutional change. The key institutional innovations were national 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). Funding for these new institutions was provided mainly by the public sector in the first half of the century. 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 USA, the private sector played a central role from the beginning in the development of agricultural machinery.

The contributions of the international agricultural research centers, in particular the Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) in Mexico and the International Rice Research Institute (IRRI) in the Philippines, were essential. Their strategy for increasing the productivity of food crops was based explicitly on the premise that, given appropriate institutional mechanisms, technology spillovers across political and agro-climatic boundaries can be captured. In addition, high rates of investment in national crop research, infrastructure, and market development combined with appropriate policy support fueled the resulting growth in land productivity (Pingali and Heisey 2001).

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 increasing importance of molecular biology and genetic engineering. Finally, the trade in agricultural inputs and outputs is becoming more open in nearly all countries. These developments have created a powerful new set of incentives for investment in private research that has changed the structure of the public/private agricultural research endeavor, particularly with respect to crop improvement (Falcon and Fowler 2002, Pingali and Traxler 2002).

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.

Climate variability and change

Earth's climate system has changed since the preindustrial era, in part because of human activities, and this change is projected to continue throughout the 21st century. During the last 100 yr, the mean global surface temperature has increased by about 0.6°C (see Fig. 12). Precipitation increased by 0.5–1% per decade in the 20th century over most

middle and high latitudes of the continents of the Northern Hemisphere but decreased over much of the subtropical land areas at a rate of about 0.3% per decade, although it appeared to recover in the 1990s. Average sea level rose 0.1–0.2 m across the world. There was a widespread retreat of mountain glaciers in nonpolar regions, with 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 the ice covers of lakes and rivers in the middle and high latitudes of the Northern Hemisphere. Also in the Northern Hemisphere, the extent of the sea ice in the spring and summer has decreased by about 10–15% since the 1950s.

Carbon dioxide (CO₂) is the most important greenhouse gas, with methane and nitrous oxides as other contributors. Since 1750, the atmospheric concentration of CO₂ has increased by about 32% (Houghton et al. 2001). Nearly 80% of the increase during the past 20 yr is because of fossil fuel burning, and the rest is attributed to land-use changes, especially deforestation, and to a lesser extent to cement production. Atmospheric concentrations of methane have increased by a factor of 2.5 since 1750 (from about 700 to 1750 ppb), and they continue to increase (Houghton et al. 2001). The atmospheric concentration of nitrous oxide has increased by about 17% since 1750 or from about 270 to 315 ppb (Houghton et al. 2001).

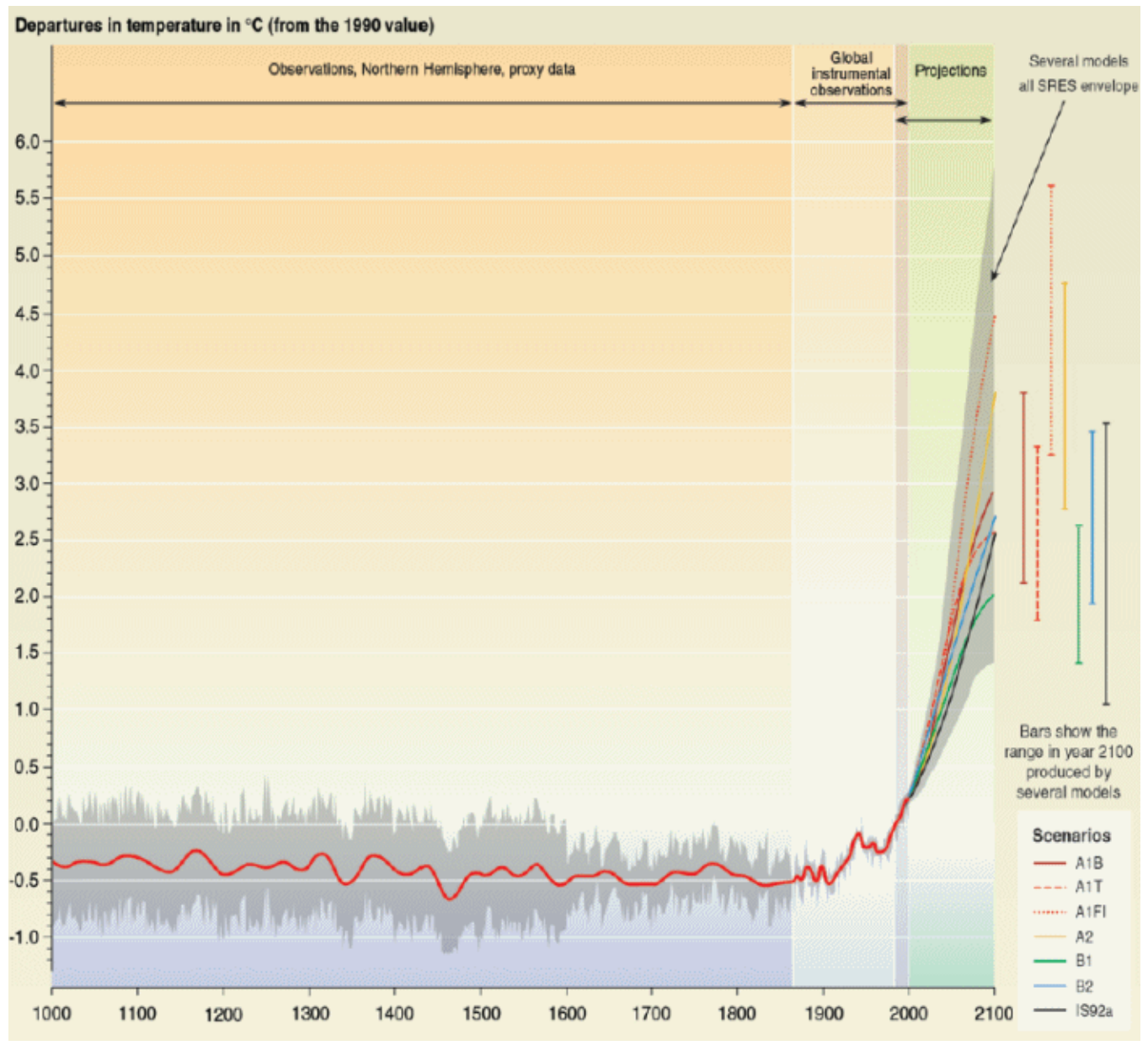
The global mean surface temperature is projected to increase 1.4–5.8°C between 1990 and 2100 (Houghton et al. 2001). Precipitation patterns are projected to change, with most arid and semiarid areas becoming drier and with an increase in heavy precipitation events, leading to an increased incidence in floods and drought.

Nutrient application to agricultural systems

Plant nutrients are essential for food production, but current methods of fertilizer use contribute to environmental problems such as greenhouse gas emissions and eutrophication. Nitrogen and phosphorus applied on farm fields to help crops grow can be carried beyond the bounds of the field to which they are applied, potentially affecting ecosystems off site.

As discussed in the science and technology section above, a key component of the technological advances in agriculture has been the rapid growth

Fig. 12. Variations in the surface temperature of the Earth from the year 1000 to 2100. SRES stands for *Special Report on Emissions Scenarios* (IPCC 2001). Source: IPCC (2002). From "Ecosystems and Human Well-being: Scenarios, Volume 2" by Steve R. Carpenter, et al., eds. Copyright (c) 2005 Millennium Ecosystem Assessment. Reproduced by permission of Island Press, Washington, D.C



in the use of nitrogenous fertilizers. By 1990, the total amount of reactive nitrogen created by human activities was about 141 Tg/yr (Table 4). This represents a ninefold increase over 1890, compared with a 3.5-fold increase in global population (Galloway and Cowling 2002).

At a global scale, cereal yields and fertilizer N consumption have increased in a near-linear fashion during the past 40 yr and are highly correlated with one another. Cereals currently account for about 56% of global N fertilizer use (IFA 2002). The ratio of global cereal production to global fertilizer N consumption has declined in the past 40 yr, giving rise to 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). 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. Increases in N consumption of 20–60% during the next 25 yr will be required to keep pace with the expected demand (Cassman et al. 2003).

A substantial portion of the nitrogen applied is not used by plants and is carried off the field in runoff. Such losses of reactive N can damage environmental services in the receiving ecosystems. Large differences in nitrogen use efficiency 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). 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 is widely used in fertilizers and as a nutrient in supplements for dairy cattle in some parts of the world. Phosphorus application has increased threefold since 1960. Unlike nitrogen, which is transported from the application site in a variety of ways, phosphorus tends to accumulate in the soil. Hence, the growth in application is accompanied by accumulation in soils, which is an indicator of the eutrophication potential of freshwater lakes and P-sensitive estuaries. Global agricultural P budgets indicate that average P accumulation in agricultural areas of the world is approximately 8×10^6 Mg/yr (see Fig. 13), but the rate of annual accumulation has begun to plateau.

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 changes in land cover can be shown to have occurred since the 1970s (Lepers et al. 2005). In this section, we summarize the results of this study, focusing on four types of land conversion: deforestation, dryland degradation, agricultural expansion and abandonment, and urban expansion.

Deforestation is the single most measured process of land-cover change at a global scale. During the industrial era, global forest area was reduced by 40%, with three quarters of this loss occurring during the last two centuries (Millennium Ecosystem Assessment 2005a). Forests have completely disappeared in 25 countries, and another 29 have lost more than 90% of their woodlands. Although forest cover and biomass in Europe and North America is currently increasing following radical declines in the past, the deforestation of natural forests in the tropics continues at an annual rate of more than 10×10^6 ha/yr. 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. Data on boreal forests are particularly limited, and the extent of change there is less well known.

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 yr or less (Dregne 2002). Approximately 10% of the drylands and hyperarid zones of the world are considered degraded, with the majority of these areas in Asia.

Most of the studies and data sets related to changes in agricultural land focus on changes in arable land and permanent crops. The cropland class, defined

Table 4. Regional creation of reactive nitrogen in the mid-1990s.

World regions	Total (tg/yr)	Per capita (kg-person ⁻¹ ·yr ⁻¹)
Africa	5.3	7
Asia	68.9	17
Europe and the former Soviet Union	26.5	44
Latin America	9.4	19
North America	28.4	100
Oceania	2.2	63
World	140.7	24

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%.

Biological invasions and diseases

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 or ecological and long-term or evolutionary consequences. In some ecosystems, invasions by alien organisms and diseases result in the extinction of native species or a huge loss in ecosystem services.

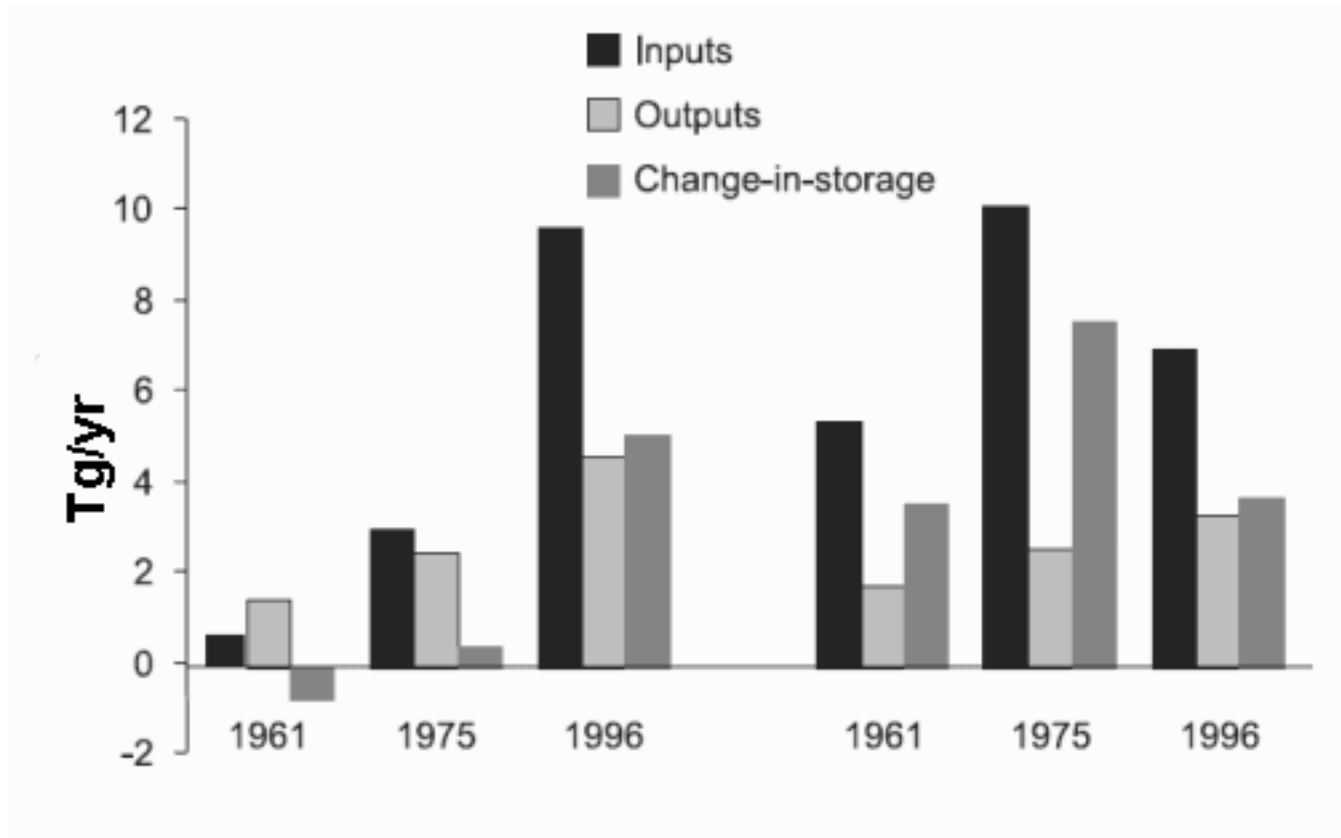
Acceleration of extinction rates as a result of negative interactions is one of the most important

consequences of biological invasions (Ehrlich and Daily 1993, Hughes et al. 1998). In the USA, invasions of non-native plants, animals, and microbes are thought to be responsible for 42% of the decline of the native species now listed as endangered or threatened (Pimentel 2002). 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).

However, introductions of alien species can also be beneficial in terms of human population. 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), a statistic likely to be repeated in most countries.

Invasive and native parasites and pathogens possess a considerable potential to significantly modify ecosystem function. This potential stems from both their diversity and their ability to multiply very rapidly. 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 yr, studies demonstrating how pathogens modify and regulate free-living hosts

Fig. 13. Estimated inputs, outputs, and change in storage of phosphorus on agricultural lands in developing and developed countries measured in Tetragrams per year. 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 because of greatly reduced use in the former Soviet Union and Eastern Europe (Bennett et al. 2001). From "Ecosystems and Human Well-being: Scenarios, Volume 2" by Steve R. Carpenter, et al., eds. Copyright (c) 2005 Millennium Ecosystem Assessment. Reproduced by permission of Island Press, Washington, D.C.



have completely altered our understanding of the role that parasites play in natural and human-modified systems (see, for example, Grenfell and Dobson 1995).

CONCLUDING REMARKS

This paper focuses on drivers of ecosystem change. Individual drivers interact with other drivers and with ecosystems in a complicated dance, of which we know only a few basic steps. The scenario results, which are reported in later papers in this issue, report on our attempts to outline possible

outcomes. We conclude this paper with a brief overview of the range of values of drivers in the scenarios and encourage readers interested in more details to download the technical volume at the Millennium Ecosystem Assessment Web site (www.MAWeb.org).

Demographic drivers

The range of population values in the scenarios is $8.1\text{--}9.6 \times 10^9$ in 2050 and $6.8\text{--}10.5 \times 10^9$ in 2100 (see Fig. 1). The Order from Strength scenario generally assumes high fertility and high mortality;

the Global Orchestration scenario generally assumes low fertility and low mortality.

Economic drivers

The Millennium Ecosystem Assessment (MA) scenarios include a rich set of economic drivers. A useful summary statistic is the differences across scenarios in growth rates in total and per capita income. Per capita income doubles or quadruples between 2000 and 2050, depending on scenario, whereas total economic output increases three to six times.

Sociopolitical, cultural, and religious drivers

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. The Global Orchestration scenario emphasizes international cooperation and global flows of capital and research, whereas Order from Strength sees a reduction in all forms of international transactions.

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.

Scientific and technological drivers

The MA scenarios include a myriad of different drivers in the fields of science and technology. Generally, the Global Orchestration and TechnoGarden scenarios have the fastest technological change across a range of industries. Adapting Mosaic has slower technological advance initially, but more environmentally friendly improvements occur as the fruits of the best local solutions spread to other parts of the world.

Nutrient application in agriculture

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

Food production in the TechnoGarden scenario increases, but technical change that reduces the need for applied nutrients, so the increase in fertilizer use is the lowest in this scenario. Nutrient use in the Adapting Mosaic scenario falls in the range of that of the other scenarios.

Responses to this article can be read online at:
<http://www.ecologyandsociety.org/vol11/iss2/art29/responses/>

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LITERATURE CITED

- Anderson, K., and Y. Hayami.** 1986. *The political economy of agricultural protection: East Asia in international perspective.* Allen and Unwin, London, UK.
- Barro, R. J.** 1997. *Determinants of economic growth.* MIT Press, Cambridge, Massachusetts, USA.

- Barro, R. J., and X. Sala-i-Martin.** 2004. *Economic growth*. Second edition. MIT Press, Cambridge, Massachusetts, USA.
- Becker, G.** 1960. An economic analysis of fertility. Pages 209-231 in A. J. Coale, editor. *Demographic and economic change in developed countries*. Princeton University Press, Princeton, New Jersey, USA.
- Becker, G. S., and R. Barro.** 1988. A reformulation of the economic theory of fertility. *Quarterly Journal of Economics* 103:1-25.
- Beierle, T. C., and J. Cayford.** 2002. *Democracy in practice: public participation in environmental decisions*. Resources for the Future, Washington, D.C., USA.
- Bennett, E. M., S. R. Carpenter, and N. F. Caraco.** 2001. Human impact on erodable phosphorus and eutrophication: a global perspective. *BioScience* 51 (3):227-234.
- Bennett, M. K.** 1941. Wheat in national diets. *Wheat Studies* 18(2):37-76.
- Berhe, A. A.** 2000. *Landmines and land degradation: a regional political ecology perspective on the impacts of landmines on environment and development in the developing world*. Michigan State University, East Lansing, Michigan, USA.
- Bongaarts, J.** 1997. The role of family planning programmes in contemporary fertility transitions. Pages 422-443 in G. W. Jones, R. M. Douglas, J. C. Caldwell, and R. M. D'Souza, editors. *The continuing demographic transition*. Clarendon, Oxford, UK.
- Bongaarts, J., and S. C. Watkins.** 1996. Social interactions and contemporary fertility transitions. *Population and Development Review* 22(4):639-682.
- Caldwell, J. C.** 1982. *Theory of fertility decline*. Academic Press, London, UK.
- Carpenter, S. R., E. M. Bennett, and G. D. Peterson.** 2006 in press: Editorial: Special Feature on Scenarios for Ecosystem Services. *Ecology and Society*.
- Cassman, K. G., A. Dobermann, and D. T. Walters.** 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. *Ambio* 31 (2):132-140.
- Cassman, K. G., A. Dobermann, D. T. Walters, and H. S. Yang.** 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. *Annual Review of Environment and Resources* 28:315-358.
- Cleland, J., and C. Wilson.** 1987. Demand theories of the fertility transition: an iconoclastic view. *Population Studies* 41(1):5-30.
- Cohen, B.** 1998. The emerging fertility transition in sub-Saharan Africa. *World Development* 26 (8):1431-1461.
- Cohen, J. E.** 2003. Human population: the next half century. *Science* 302:1172-1175.
- David, C., and K. Otsuka, editors.** 1994: *Modern rice technology and income distribution in Asia*. Lynne Rienner, Boulder, Colorado, USA.
- de Moor, A.** 2002. The perversity of government subsidies for energy and water. Page 368 in J. P. Cinch, K. Schlegelmilch, R.-U. Sprenger, and U. Triebswetter, editors. *Greening the budget: budgetary policies for environmental improvement*. Edward Elgar, Cheltenham, UK.
- de Vries, B., and J. Goudsblom, editors.** 2002. *Mappae mundi: humans and their habitats in a long-term socio-ecological perspective*. Amsterdam University Press, Amsterdam, The Netherlands.
- Dietz, T., E. Ostrom, and P. C. Stern.** 2003. The struggle to govern the commons. *Science* 301:1907-1912.
- Dobson, A. P., P. J. Hudson, and A. M. Lyles.** 1992. Macroparasites: worms and others. Pages 329-342 in M. J. Crawley, editor. *Natural enemies: the population biology of predators, parasites and diseases*. Blackwell Scientific, Oxford, UK.
- Dollar, D., and P. Collier.** 2001. *Globalization, growth, and poverty: building an inclusive world economy*. Oxford University Press, Oxford, UK.
- Dosi, G., K. Pavitt, and L. Soete.** 1990: *The economics of technical change and international trade*. Harvester Wheatsheaf, London, UK.

- Dregne, H.** 2002. Land degradation in the drylands. *Arid Land Research and Management* **13**:99-132.
- Dunlap, R. E., and A. G. Mertig.** 1995. Global concern for the environment: Is affluence a prerequisite? *Journal of Social Issues* **51** (4):121-137.
- Dunlap, R. E., G. H. J. Gallup, and A. M. Gallup.** 1993. Global environmental concern: results from an international public opinion survey. *Environment* **35**:7-15, 33-39.
- Easterlin, R. A.** 1969. Towards a socio-economic theory of fertility. Pages 127-156 in S. J. Behrman, L. Corsa, and R. Freedman, editors. *Fertility and family planning: a world view*. University of Michigan Press, Ann Arbor, Michigan, USA.
- Easterlin, R. A.** 1975. An economic framework for fertility analysis. *Studies in Family Planning* **6**:54-63.
- Ehrlich, P. R., and G. C. Daily.** 1993. Population extinction and saving biodiversity. *Ambio* **22**:64-68.
- Falcon, W., and C. Fowler.** 2002. Carving up the commons: emergence of a new international regime for germplasm development and transfer. *Food Policy* **27**:197-222.
- FAO.** 2004. *FAOSTAT*. Available online at <http://faostat.fao.org/default.aspx>.
- Galloway, J. N., and E. B. Cowling.** 2002. Reactive nitrogen and the world: 200 years of change. *Ambio* **31**:64-71.
- Garenne, J. V.** 2002. The timing of the fertility transition in sub-Saharan Africa. *World Development* **30**(10):1835-1843.
- Geist, H. J., and E. F. Lambin.** 2002. Proximate causes and underlying driving forces of tropical deforestation. *BioScience* **52**(2):143-150.
- Geist, H. J., and E. F. Lambin.** 2004. Dynamic causal patterns of desertification. *BioScience* **54** (9):817-829.
- Grenfell, B. T., and A. P. Dobson.** 1995. *Ecology of infectious diseases in natural populations*. Cambridge University Press, Cambridge, UK.
- Grübler, A.** 1998. *Technology and global change*. Cambridge University Press, Cambridge, UK.
- Hanada, A.** 2003. *Culture and environmental values: a comparison of Japan and Germany*. George Mason University, Fairfax, Virginia, USA.
- Hardin, G.** 1968. The tragedy of the commons. *Science* **162**:1243-1248.
- Hayami, Y., and V. W. Ruttan.** 1985. *Agricultural development: an international perspective*. Johns Hopkins University Press, Baltimore, Maryland, USA.
- Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskall, and C. A. Johnson, editors.** 2001. *Climate change 2001: the scientific basis; contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.
- Huffman, W. E., and R. E. Evenson.** 1993. *Science for agriculture: a long-term perspective*. Iowa State University Press, Ames, Iowa, USA.
- Hughes, J. B., G. C. Daily, and P. R. Ehrlich.** 1998. The loss of population diversity and why it matters. Pages 71-83 in P. H. Raven, editor. *Nature and human society*. National Academy Press, Washington, D.C., USA.
- Inglehart, R.** 1995. Public support for environmental protection: objective problems and subjective values in 43 societies. *PS: Political Science and Politics* **15**:57-71.
- International Civil Aviation Organization (ICAO).** 1995. *Civil aviation statistics of the world, 1994*. Document no. 9180/20. IOAC, Montreal, Quebec, Canada.
- International Fertilizer Industry Association (IFA).** 2002. *Fertilizer use by crop*. Fifth edition. FAO, Rome, Italy.
- International Panel on Climate Change (IPCC).** 2001. *Special report on emissions scenarios*. IPCC, Geneva, Switzerland.
- International Panel on Climate Change (IPCC).** 2002. *Climate change 2001: synthesis report*. Cambridge University, Cambridge, UK.

Jones, S. 2002. A framework for understanding on-farm environmental degradation and constraints to the adoption of soil conservation measures: case studies from highland Tanzania and Thailand. *World Development* 30(9):1607-1620.

Kluckholm, C. 1952. Values and value-orientation in the theory of action: an exploration in definition and classification. Pages 395-418 in T. Parsons and E. Shils, editors. *Toward a general theory of action*. Harvard University Press, Cambridge, Massachusetts, USA.

Knodel, J., and E. van der Walle. 1979. Lessons from the past: policy implications of historical fertility studies. *Population and Development Review* 5(2):217-245.

Lambin, E. F., B. L. Turner II, H. J. Geist, S. B. Agbola, A. Angelsen, J. W. Bruce, O. Coomes, R. Dirzo, G. Fischer, C. Folke, P. S. George, K. Homewood, J. Imbernon, R. Leemans, X. Li, E. F. Moran, M. Mortimore, P. S. Ramakrishnan, M. B. Richards, H. Skånes, W. L. Steffen, G. D. Stone, U. Svedin, T. A. Veldkamp, C. Vogel, and J. Xu. 2001. The causes of land-use and land-cover change: moving beyond the myths. *Global Environmental Change* 11(4):261-269.

Lee, R. 2003. The demographic transition: three centuries of fundamental change. *Journal of Economic Perspectives* 17:167-190.

Leichenko, R. M., and K. O'Brien. 2002. The dynamics of rural vulnerability to global change: the case of Southern Africa. *Mitigation and Adaptation Strategies for Global Change* 7(1):1-18.

Lepers, E., E. F. Lambin, A. C. Janetos, R. DeFries, F. Achard, N. Ramankutty, and R. J. Scholes. 2005. A synthesis of rapid land-cover change information for the 1981-2000 period. *BioScience* 55(2):115-124.

Lutz, W., and A. Goujon. 2001. The world's changing human capital stock: multi-state population projections by educational attainment. *Population and Development Review* 27(2):323-339.

Lutz, W., B. C. O'Neill, and S. Scherbov. 2003. Europe's population at a turning point. *Science* 299:1991-1992.

Lutz, W., W. Sanderson, and S. Scherbov. 2001. The end of world population growth. *Nature* 412:543-545.

Mack, R. N., D. Simberloff, W. M. Lonsdale, H. Evans, M. Clout, and F. A. Bazzaz. 2000. Biotic invasions: causes, epidemiology, global consequences, and control. *Ecological Applications* 10:689-710.

Maddison, A. 1991. *Dynamic forces in capitalist development*. Oxford University Press, Oxford, UK.

Maddison, A. 1995. *Monitoring the world economy, 1820-1992*. OECD, Paris, France.

Maddison, A. 2003. *The world economy: historical statistics*. OECD, Paris, France.

Millennium Ecosystem Assessment. 2003. Ecosystems and their services. Pages 49-70 in Millennium Ecosystem Assessment. *Ecosystems and human well-being*. Island Press, Washington, D.C., USA.

Millennium Ecosystem Assessment. 2005a. *Ecosystems and human well-being. Volume 1. Current state and trends*. Island Press, Washington, D.C., USA.

Millennium Ecosystem Assessment. 2005b. *Ecosystems and human well-being. Volume 2. Scenarios*. Island Press, Washington, D.C., USA.

Moll, H. C. 1989. *Aanbod van en vraag naar metalen; ontwikkelingen, implicaties en relaties; een methodische assesment omtrent substitutie van materialen*. University of Groningen, Groningen, The Netherlands.

Nakicenovic, N., A. Grübler, and A. McDonald, editors. 1998. *Global energy perspectives*. Cambridge University Press, Cambridge, UK.

Nelson, G. C., editor. 2001. *Genetically modified organisms in agriculture: economics and politics*. Academic Press, San Diego, California, USA.

OECD. 1997. *Reforming energy and transport subsidies*. OECD, Paris, France.

OECD. 1998. *Eco-efficiency*. OECD, Paris, France.

OECD. 2004. *OECD agricultural policies 2004 at a glance*. OECD, Paris, France.

Ostrom, E., T. Dietz, N. Dolsak, P. C. Stern, S. Stonich, and E. Weber, editors. 2002. *The drama of the commons*. National Academy Press, Washington, D.C., USA.

Pimentel, D. 2002. *Economic costs of biological invasions: biological invasions; economic and environmental costs of alien plant, animal, and microbe species*. CRC Press, Boca Raton, Florida, USA.

Pingali, P. 2004. *Westernization of Asian diets and the transformation of food systems: implications for research and policy*. ESA Working Paper No. 04-17, FAO, Rome, Italy.

Pingali, P., and G. Traxler. 2002. Changing locus of agricultural research: Will the poor benefit from biotechnology and privatization trends? *Food Policy* 27:223-238.

Pingali, P. L., and P. W. Heisey. 2001. Cereal-crop productivity in developing countries: past trends and future prospects. Pages 56-82 in J. M. Alston, P. G. Pardey, and M. Taylor, editors. *Agricultural science policy*. Johns Hopkins University Press, Baltimore, Maryland, USA.

Pingali, P. L., and S. Rajaram. 1999. Global wheat research in a changing world: options for sustaining growth in wheat productivity. Pages 1-18 in P. L. Pingali, editor. *CIMMYT 1998-99 world wheat facts and trends. Global wheat research in a changing world: challenges and achievements*. Centro Internacional de Mejoramiento de Maíz y Trigo, Mexico City, Mexico.

Ramankutty, N., and J. A. Foley. 1998. Characterising patterns of global land use: an analysis of global cropland data. *Global Biogeochemical Cycles* 12:667-685.

Renkow, M. 1993. Differential technology adoption and income distribution in Pakistan: implications for research resource allocation. *American Journal of Agricultural Economics*, 75 (1):33-43.

Rokeach, M. 1968. *Beliefs, attitudes and values: a theory of organization and change*. Jossey-Bass, San Francisco, California, USA.

Rokeach, M. 1973. *The nature of human values*.

Free Press, New York, New York, USA.

Rosa, E. A., N. Matsuda, and R. R. Kleinhesselink. 2000. The cognitive architecture of risk: pancultural unity or cultural shaping? Pages 185-210 in O. Renn and B. Rohrmann, editors. *Comparative risk perception*. Kluwer, Dordrecht, The Netherlands.

Rosen, C., editor. 2002. *World resources 2002–2004: decisions for the Earth: balance, voice, and power*. UNDP, UNEP, World Bank, World Resources Institute, Washington, D.C., USA.

Ruttan, V. R. 2001. *Technology, growth and development*. Oxford University Press, New York, New York, USA.

Schipper, L. J. 1996. *Excel spreadsheets containing transport energy data, PASSUM.XLS and FRTSUM.XLS. Versions of 9 February 1996*. International Energy Agency, Paris, France, and Lawrence Berkeley National Laboratory, Berkeley, California, USA.

Schwartz, S. H. 1992. Universals in the content and structure of values: theoretical advances and empirical tests in 20 countries. *Advances in Experimental Social Psychology* 25:1-65.

Semken, H. A. 1983. Holocene mammalian biogeography and climatic change in the eastern and central United States. Pages 182-207 in H. E. Wright, editor. *Late Quaternary environments of the United States. Volume 2. The Holocene*. University of Minnesota Press, Minneapolis, Minnesota, USA.

Smith, K. R., and S. Mehta. 2003. The burden of disease from indoor air pollution in developing countries: comparison of estimates. *International Journal of Hygiene and Environmental Health* 206:279 - 289.

Stern, P. C., T. Dietz, T. Abel, G. A. Guagnano, and L. Kalof. 1999. A social psychological theory of support for social movements: the case of environmentalism. *Human Ecology Review* 6:81-97.

Tilman, D., K. G. Cassman, P. A. Matson, R. L. Naylor, and S. Polasky. 2002. Agricultural sustainability and intensive production practices. *Nature* 418:671-677.

Tilton, J. E. 1990. *World metal demand: trends and prospects*. Resources for the Future, Washington, D.C., USA.

UN. 2002. *World population prospects: the 2000 revision. Volume 3: analytical report*. ST/ESA/SER.A/200. UN, New York, New York, USA.

UN. 2003a. *Population, education and development: the concise report*. ST/ESA/SER.A/226. UN, New York, New York, USA.

UN. 2003b. *World population in 2300*. ESA/P/WP.187. UN, New York, New York, USA.

USDA. 2001. *Oil crops situation and outlook yearbook*. Economic Research Service, U.S. Department of Agriculture, Washington, D.C., USA.

van Vuuren, D. P., B. J. Strengers, and H. J. M. De Vries. 1999. Long-term perspectives on world metal use: a systems dynamics model. *Resources Policy* 25(4):239-255.

Waggoner, P. E. 1996. How much land can ten billion people spare for Nature? *Daedalus* 125(3):73-93.

Watson, R., M. C. Zinyowera, and R. Moss, editors. 1996. *Climate change 1995. Impacts, adaptations and mitigation of climate change: scientific analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.

World Bank. 2002. *World development indicators, 2002*. World Bank, Washington, D.C., USA.

World Bank. 2003. *World development indicators, 2003*. World Bank, Washington, D.C., USA.

World Resources Institute. 1997: *World resources 1996-97*. Washington, D.C., USA.

World Trade Organization (WTO). 2002. *International trade statistics 2002*. WTO, Geneva, Switzerland.

World Trade Organization (WTO). 2003. *Understanding the WTO*. WTO, Geneva, Switzerland. Available online at: http://www.wto.org/English/thewto_e/whatis_e/tif_e/utw_chap1_e.pdf

York, R., E. Rosa, and T. Dietz. 2003. STIRPAT, IPAT and ImPACT: analytic tools for unpacking the driving forces of environmental impact. *Ecological Economics* 46:351-365.

Young, O. R. 2002. *The institutional dimensions of environmental change: fit, interplay and scale*. MIT Press, Cambridge, Massachusetts, USA.