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The Millennium Ecosystem Assessment: Tradeoffs between Food Security and the Environment*

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Abstract: This paper provides an overview of selected trends and conditions of ecosystem services, in particular, food production and impacts on the environment based on the Millennium Ecosystem Assessment. It then describes outcomes for future ecosystem services under alternative development pathways, with a focus on tradeoffs between food security and the environment, such as implications for fertilizer use, and the role of biofuels. As tradeoffs among various ecosystem services are expected to increase into the future, research will need to focus increasingly on ways to achieve a balance between food security and improving non-food ecosystem services. To reduce adverse future impacts, research is urgently needed in the areas of land use change impacts on ecosystems and biodiversity, mitigation strategies for climate change, enhancing water security, and for hot spot regions where ecosystem services and human well-being are particularly vulnerable, including Sub-Saharan Africa, South Asia, and the Middle East and North Africa region.

Key Words: Ecosystem services, food security, tradeoffs, Millennium Ecosystem Assessment

Introduction

Food supply (and demand) is intrinsically linked with its surrounding environment. The interlinkages among ecosystem services, including the provision of food and water, their future development, and implications for human well-being and food security, were recently assessed as part of the Millennium Ecosystem Assessment (MA, 2003; MA, 2005a). Ecosystem services, which are the benefits people obtain from ecosystems, include supporting, provisioning, regulating, and cultural services. Supporting services include nutrient cycling, soil formation, and primary production. Provisioning services, or goods produced by ecosystems, include food, feed, fiber, and freshwater. Regulating services affect ecosystem processes, such as air quality or soil erosion, climate, and pests. Finally, cultural services, which are non-material benefits, include aesthetic values of a landscape, and recreation benefits. Changes in the interlinkages and tradeoffs among the various ecosystem services and the future direction of these services will have important outcomes for human well-being. Drivers of change impose or relieve stresses on ecosystem services, and how these drivers change over time will be crucial for future human well-being and levels of poverty.

This paper provides a brief overview of selected trends and conditions of ecosystem services, describes potential outcomes for future ecosystem services under alternative development pathways, and concludes with implications for tradeoffs between food security and the environment.

Assessment of Selected Trends and Conditions of Ecosystem Services

Over the last 50 years, ecosystems have been changed through human intervention more rapidly and extensively than in any comparable period before. Some of the main drivers determining changes and outcomes in ecosystem services over the past 100 years have been rapid

* The paper draws heavily on the results of the Millennium Ecosystem Assessment. For details see http://www.millenniumassessment.org.
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population and economic growth. Between 1960 and 2000, the world population doubled from 3 to 6 billion people, and the global economy increased more than 6-fold. To meet rapidly growing food demands, food production more than doubled, water use increased rapidly, wood harvests for pulp and paper production tripled, overall timber production increased by more than half, and installed hydropower capacity doubled. To meet tremendous increases in food demand, food producing areas were expanded significantly and other natural resources, particularly freshwater, fish, and timber, were exploited at increasing fractions of available supply (MA, 2005a, 2005b). In the last 50 years, significant increases in provisioning ecosystem services were also achieved through productivity increases. The 'green revolution' in food production propelled the adoption of high-yielding cereal varieties supported by rapid increases in irrigated areas and fertilizer use, particularly in Asia. Outcomes of the green revolution are reflected in declines in international food prices, and slowing conversion of further forest and other areas into agricultural production. Productivity increases have been much slower in Sub-Saharan Africa, and are increasingly constrained in the Middle East and North Africa due to water scarcity. Despite rapid increases in food production and other provisioning ecosystem services, nutrition levels in many parts of the world and particularly in Sub-Saharan Africa have stayed at unacceptably low levels. In 1997, Sub-Saharan Africa had more malnourished children than in the mid-1970s. The West Asia and North Africa region also experienced a worsening of child malnutrition, and while Asia has seen dramatic improvements in food security large pockets of undernutrition remain, particularly in South Asia, but also in parts of Southeast and East Asia (Rosegrant et al., 2001).

What are the outcomes of improvements in provisioning services for other ecosystem services? According to the Millennium Ecosystem Assessment, approximately 60% of all ecosystem services are degraded, often at the expense of enhanced provisioning services. Cultivated systems, defined as areas in which at least 30% of the landscape is cultivated, now cover 24% of the terrestrial surface. Areas cultivated for food production have taken over space previously occupied by a range of forest covers, ranging from Mediterranean forests, woodlands, and scrub, temperate, tropical, and sub-tropical dry broadleaf forests, and flooded grasslands and savannahs, among others. At the same time, rates of species extinction have accelerated, freshwater ecosystems are degraded, and some freshwater capture fisheries have collapsed. Genetic diversity of cultivated species has declined, and the first impacts of climate change on all ecosystem services have become apparent (MA, 2005a, 2005b). Human activities have roughly doubled the rate of creation of reactive nitrogen on land surfaces, and most of this increase has been very recent. The use of phosphorus fertilizers increased nearly 3-fold between 1960 and 1990 but has slowed since.

In terms of hotspot areas, dryland areas appear to be particularly vulnerable to further environmental degradation. They are defined as land where plant production is limited by water availability and account for 40% of total terrestrial area, but only 7% of global freshwater resources. Dryland areas are home to 2 billion people, 90% of whom reside in developing countries with access to limited water supply and sanitation and other infrastructure and low soil organic matter content (MA, 2005a).

Why should we worry about the significant degradation of some ecosystem services? The Millennium Ecosystem Assessment points to several challenges that increasingly degraded ecosystems and their services pose for humanity: First, some ecosystem services that we have enjoyed in the past, such as clean air, some recreational services, and species variety and diversity are increasingly out of reach for some (generally poor) people, and others of importance to human well-being such as freshwater supplies, or sufficient food of high quality, are being increasingly constrained or adversely affected by degraded ecosystem services. Second, the likelihood of nonlinear changes to ecosystems might well increase. Examples of such nonlinear changes include disease outbreaks linked to changing weather patterns, such as cholera outbreaks linked to the 1997-98 El Niño, extensive eutrophication and hypoxia of freshwater and coastal ecosystems, changes in regional climate patterns as a result of passing thresholds in deforestation, and fisheries collapses of commercially important food fish. Third, degraded ecosystem services contribute to growing inequities between the poor and the rich, as the poor tend to live in ecosystems that pose more challenges for healthy and productive lives, such as dryland areas, and are often caught in adverse spirals of environmental degradation and poverty increases (MA, 2005a).

Millennium Ecosystem (MA) Scenarios - Outcomes for Future Ecosystem Services, with a Focus on Food Supply and Related Outcomes

In order to assess future constraints to ecosystem services 4 plausible alternative futures of the world focusing on alternative pathways for sustaining ecosystem services were developed combining qualitative storylines with quantified scenarios. These scenarios explore the outcomes of increased globalization versus increased regionalization, on the one hand, and reactive versus proactive management of ecosystems and their services, on the other hand.

The Global Orchestration (GO) scenario envisions a globally connected society that focuses on global trade and economic liberalization and takes a reactive approach to ecosystem problems, but also takes strong steps to reduce poverty and inequality and to invest in public goods such as infrastructure and education. The Order from Strength (OS) scenario depicts a regionalized and fragmented world, concerned with security and protection, emphasizing primarily regional markets, paying little attention to public goods, and taking a reactive approach to ecosystem problems. In the Adapting Mosaic (AM) scenario regional watershed-scale ecosystems are the focus of political and economic activity. Local institutions are strengthened and local ecosystem management strategies are common. Moreover, societies develop a strongly proactive approach to the management of ecosystems. The TechnoGarden (TG) scenario presents a globally connected world relying strongly on environmentally sound technology, using highly managed, often engineered, ecosystems to deliver ecosystem services, and taking a proactive approach to the management of ecosystems in an effort to avoid problems. For additional storyline details, see MA (2005c).

Selected storyline parameters were quantified (for a list of agriculture-related parameters, see Table 1), and then analyzed with the help of a suite of soft-linked, state-of-the-art global models covering different aspects of the global economic-environment system (Box 1), including IFPRI's IMPACT food projections model. Both storylines and quantitative projections were developed out to 2050, with selected results to 2100 to account for longer-term change processes, such as climate change, deforestation, and biodiversity loss.

Outcomes for food supply and demand

All scenarios show small increases in total food consumption per person, going up fastest in the Global Orchestration (GO) scenario because of higher income growth and greater average per capita purchasing power. However, direct consumption of cereals as food declines under both the Adaptive Mosaic (AM) and Order from Strength (OS) scenarios (Figure 1). Per capita demand for livestock products is expected to increase much more rapidly worldwide, driven by strong income growth and increasing preference for livestock products. Globally, annual per capita consumption is expected to increase from 36 kg in 1997 to 70 kg by 2050 under the GO scenario, and still to 43 kg under the TG (with low meat preference in developed countries), and 41 kg under the AM and OS scenarios where higher populations and lower income growth make meat products less affordable, particularly in developing countries. Under the GO scenario, increases in demand are largest in Asia, the Former Soviet Union (FSU) region, and the OECD, whereas Sub-Saharan Africa and the West Asia/North Africa (WANA) region are unlikely to experience significant increases in per capita meat consumption, reaching levels of only 27 kg and 34 kg, respectively, by 2050 (compared to 88 kg capita^{-1} in the OECD in 1997) (Figure 2).

Global cereal production increases compared to 1997 baseline values under all 4 scenarios. The GO scenario shows the largest increase at 73% (from 1872 million tons to 3230 million tons), followed by TG at 57%, OS at 55%, and AM at 53%. The largest production increase in Sub-Saharan Africa is achieved under the GO scenario, with production increasing from 81 million tons in 1997 to 305 million tons by 2050, driven by rapid income and investment growth under the GO scenario, but increases are substantial under all scenarios, due to faster income growth, and other developments envisioned under TG (strong technology growth), AM (area and yield growth through adaptive management) and OS (population growth, stronger reliance on basic staple crops).

On a per capita and regional basis, however, food production increases vary considerably. As a result of growing water scarcity and limited land availability, coupled with growing populations and incomes, cereal production on a per capita basis would decline in the West Asia and North Africa region from 249 kg capita^{-1} in the base year to 241 kg capita^{-1} under the GO scenario and

Table. Selected agriculture related parameter changes, Millennium Ecosystem scenarios.

Parameter	Global Orchestration	TechnoGarden	Adaptive Mosaic	Order from Strength
Nonagricultural income growth	High income growth 2020-2050: 3.0% $year^{-1}$ 2050-2100: 2.3% $year^{-1}$	Medium income growth (increasing) 2020-2050: 2.5% $year^{-1}$ 2050-2100: 2.3% $year^{-1}$	Medium/low growth, improving over time 2020-2050: 1.9% $year^{-1}$ 2050-2100: 1.9% $year^{-1}$	Medium income growth in developed countries, low growth in developing countries 2020-2050: 1.0% $year^{-1}$ 2050-2100: 1.3% $year^{-1}$
Population growth	Low population growth 2050: 8.1 billion people 2100: 6.1 billion people	Medium population growth 2100: 8.8 billion people 2100: 8.6 billion people	Somewhat high population growth 2050: 9.5 billion people 2100: 9.8 billion people	High population growth 2050: 9.6 billion people 2100: 10.5 billion people
Investments	High investment in human and physical capital	High investment in human, physical, and natural capital	Medium-level investments, social areas	Medium-level investments in developed countries, low in developing countries
Technological change	Medium-high	Medium, increasing	Medium/low	Low
Irrigated area growth	Significant irrigated area expansion, high efficiency growth	Some irrigated area expansion in developing countries, high efficiency improvement	No irrigated area expansion, low to medium efficiency improvement	Low irrigated area growth and low efficiency improvement
Other agricultural parameters	Medium-high yield growth, full trade liberalization, high meat demand	Medium-high yield growth in developing countries, low growth in developed countries (organic farming), full trade liberalization, low meat demand in developed countries	Medium, decreasing yield growth in developed countries, medium-low, increasing in developing, low meat demand, existing trade protection levels, maybe decline in the future	Low yield growth improvements High meat demand in developed countries, low in developing countries Increasing trade protection

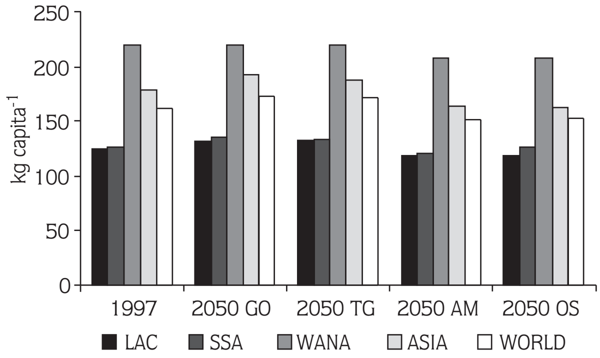
Source: IFPRI-IMPACT parameters for the MA.

Box 1 - Models used in global modeling exercise.

The models in the global modeling exercise include:

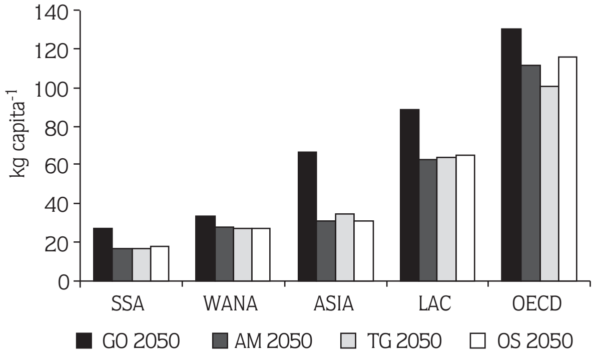
- The IMPACT model of the International Food Policy Research Institute in the United States, which computes food supply, demand, trade, and international food prices for countries and regions (Rosegrant et al., 2001).
- The WaterGAP model of the University of Kassel in Germany, which computes global water use and availability on a watershed scale (Alcamo et al., 2003).
- The AIM global change integrated model of the National Institute for Environment Studies in Japan, which computes land cover and other indicators of global change worldwide, with an emphasis on Asia (Kainuma et al., 2002).
- The IMAGE 2.2 global change model of the National Institute of Public Health and the Environment in the Netherlands, which computes climate and global land cover on a grid scale and several other indicators of global change (Alcamo et al., 1998; IMAGE-team, 2001).
- The Ecopath with Ecosim model of the University of British Columbia in Canada, which computes dynamic changes in selected marine ecosystems as a function of fishing efforts (Pauly et al., 2000).
- Aquatic Freshwater Biodiversity model developed as part of the Millennium Ecosystem Assessment; identifies changes in the number of fish species on a river basin scale as a function of changing river runoff (Sala et al., 2005, Xeonoupoulus et al., 2005).
- Terrestrial Biodiversity model developed as part of the Millennium Ecosystem Assessment; computes aggregated changes in terrestrial biodiversity as a function of loss of habitat, climate change, nitrogen deposition, and introduction of alien species (Sala et al., 2005).

Sources: MA (2005c); Alcamo et al. (2005).



Source: IMPACT simulations (for the MA).

Figure 1. Per capita availability of cereals as food, 1997 and projected 2050, Millennium Ecosystem Assessment scenarios.



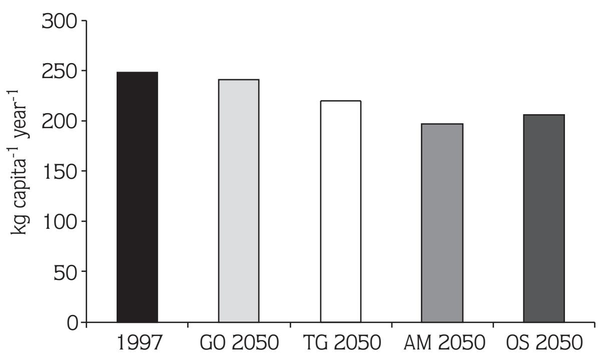
Source: IMPACT simulations (for the MA).

Figure 2. Per capita meat demand, projected 2050, Millennium Ecosystem Assessment scenarios.

only 198 kg capita^{-1} under the AM scenario due to declining water availability and land suitability constraints, among others (Figure 3).

Meat production is projected to increase at a greater rate over the period for all 4 scenarios. The GO scenario experiences the greatest increase at 170% over 1997 production levels, followed by OS with an 86% increase, AM with an 85% increase, and TG with a 79% increase.

Sources of cereal production growth generally come more from yield improvement than from area expansion across all 4 scenarios. Despite this there are significant variations among scenarios and regions. Under the GO scenario, at the global level yield improvements significantly outpace area expansion, at 1.02% per year, compared to area expansion of 0.01% per year. Area growth rates are higher in Sub-Saharan Africa and Latin America, and WANA, and below the global average in Asia, and the FSU. Under the OS scenario, on the other hand, low yield growth places a larger burden on harvested area expansion. Globally, harvested area is expected to grow at 0.34% per year, while yield improvements increase at 0.48% per year. Area expansion is particularly significant in Sub-Saharan Africa, at 1.01% per year and in Latin America, at 0.57% annually (Figure 4).

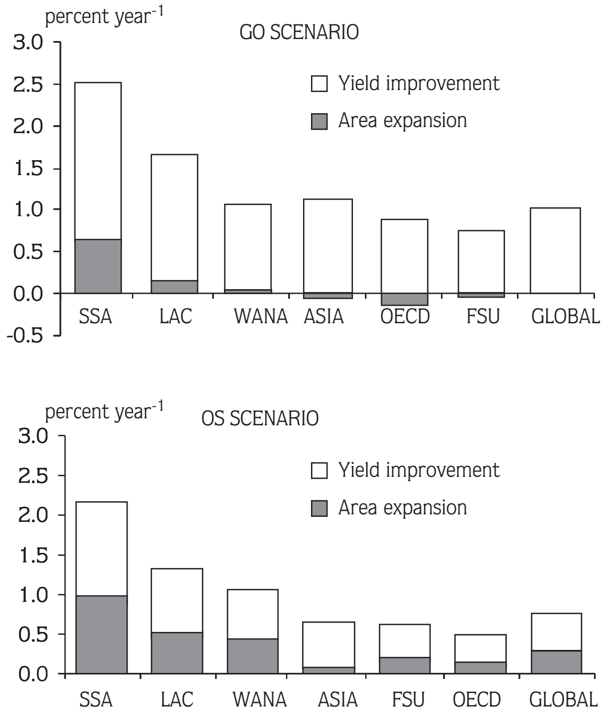


Source: IMPACT simulations (for the MA).

Figure 3. Per capita cereal production, West Asia and North Africa region, 1997 and projected 2050, Millennium Ecosystem Assessment scenarios.

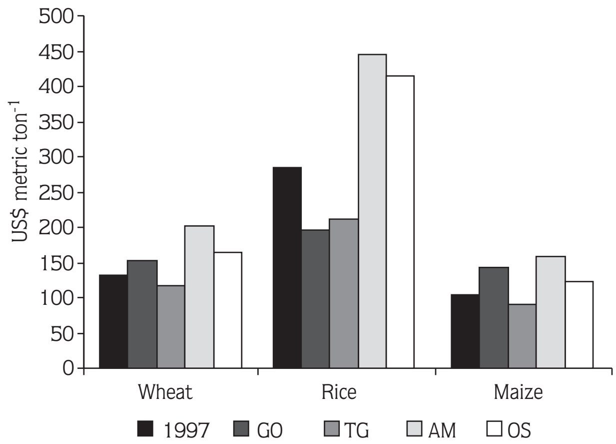
Results for food trade and international food prices

Trade liberalization under the GO scenario leads to an increase in international trade, particularly for cereals. Cereal trade in 2050 under GO is 601 million tons, compared to just 187 million tons in 1997. Other scenarios also show increased cereal trade, with similar levels across all 3 scenarios; trade under OS is 526 million tons, under AM 513 million tons, and under TG 504 million tons. World meat trade also increases significantly, from low levels in 1997. Under the GO scenario, meat trade increases much faster in relative terms, and from 9 to 68 million tons in absolute terms. Prices for wheat, maize, and rice fall under the TG scenario, due to the advances in production and trade that will outstrip increased demand. Rice prices also fall under the GO scenario due to increases in agricultural research and infrastructure, while wheat and maize prices increase



Source: IMPACT simulations (for the MA).

Figure 4. Sources of food production growth, GO and OS scenarios, 1997-2050, Millennium Ecosystem Assessment scenarios.



Source: IMPACT simulations (for the MA).

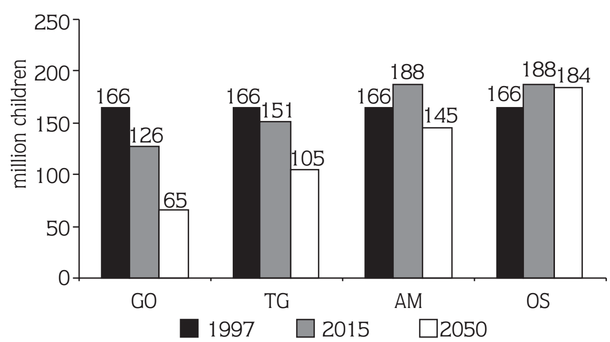
Figure 5. Projected international cereal prices for wheat, maize, and rice, 2050, Millennium Ecosystem Assessment scenarios.

following increased demand for cereals and particularly livestock products. Prices for all 3 cereals increase under both the AM and OS scenarios, with particularly large increases for rice. These price hikes tend to result from lower investments in agriculture and high population growth, along with depressed demand for cereals (Figure 5).

Implications for child malnutrition levels

Food consumption together with the quality of maternal and child care and health and sanitation are important determinants for child malnutrition outcomes. Malnutrition is the largest single contributor to disease, and inadequate nutrition of mothers and young children alone is responsible for 10% of the global burden of disease. More than half of all childhood deaths are associated with underweight, and malnourished children who survive into adulthood are more likely to suffer from chronic illness and disability, and have a higher probability of having a reduced physical and intellectual productivity (Pelletier et al., 1994; De Onis et al., 2004).

The outlook for malnourished children improves under the GO and TG scenarios. Under the GO scenario, the total number of malnourished children in developing countries declines by 24% in 2015 to 126 million children, and by 61% in 2050. Under the TG scenario, the number of malnourished children declines by 9% in 2015 and by 37% in 2050. In the Adaptive Mosaic scenario, the number of malnourished children increases to 193 million children by 2020 followed by a decline to 145 million, 22 million less than in 1997. The Order from Strength scenario only achieves a reduction to 184 million children by 2050, which is still 18 million above the base year (Figure 6).



Source: IMPACT simulations (for the MA).

Figure 6. Number of malnourished children, 1997, 2015, and projected 2050, Millennium Ecosystem Assessment scenarios.

Despite the achievements under the GO and TG scenarios, the Millennium Development Goal target of halving the proportion of malnourished children between 1990 and 2015 cannot be reached under these scenarios with both scenarios resulting in 26.5% of pre-school children in developing countries still malnourished in 2015 compared to the target rate of 15.1%.

Outcomes for food versus biofuel production

Modern biofuels include alcohol derived from fermenting maize and sugar cane, fuel oil coming from rape seed, fast-growing tree species that provide fuel for power-generating turbines, and agricultural wastes, burned to generate power. While fuelwood has been steadily replaced by other energy carriers, it still accounts for a large percentage of total energy use in some places. The level of biofuel use affects the type and distribution of land cover and the services provided by forest and other land cover types.

The TechnoGarden scenario assumes that society will be convinced that environmental degradation decreases human well-being and therefore supports long-term reductions of greenhouse gases and other air pollutant emissions. To mitigate climate change, the international community adopts a goal of limiting global mean temperature increase to 2° C by 2100 over pre-industrial levels (similar to the current target for climate policy in the EU and several European countries). Since emissions stem mostly from energy use, this requires a reduction in the use of fossil fuels, which is brought about by energy efficiency, increasing use of "zero-carbon" energy sources (modern biofuels and solar and wind energy, as examples), and more low-carbon fuels (principally natural gas). While the overall contribution to energy remains small, the impact on land use and land cover changes can be substantial.

Biofuels are considered neutral in terms of greenhouse gas emissions. Under GO, the biofuel use increases by a factor of 6, mostly driven by cost increases of fossil fuels, combined with land availability as crop production increases are achieved, chiefly through yield enhancements. Under TG, biofuel production increases by a factor of 4, mostly driven by climate policy, dampened somewhat by lower energy demand. Under OS, energy crops compete with food crops for land, raising production costs. Not taken into account in these calculations are possible long-term declines in productivity of biofuel crops, which tend to degrade soils faster and require large amounts of fertilizer and other inputs (MA, 2005c).

Outcomes for fertilizer N use and nitrogen loads to rivers

Several projections of fertilizer use have been carried out in recent years. Some of these are presented in Box 2 and Figure 7. While all projections indicate increased nitrogen fertilizer use, outcomes vary significantly depending on underlying assumptions, with increases to 2020 ranging from 10% to 80%. For the MA scenarios, based on current insights in changes in nitrogen efficiency and agricultural scenarios, we expect the outcomes for the GO scenario at about 110 million metric tons in 2020 and 120 to 140 million metric tons by 2050. The TG scenario results in somewhat lower nitrogen fertilizer use, due to increased nutrient use efficiency, and somewhat lower demand. Estimates for this scenario are use of about 100 million metric tons to 2020 and 110-120 million metric tons by 2050. The AM scenario is expected to be in between these extremes, while fertilizer use under OS would be close to the GO scenario. Clearly, there are important uncertainties in projections, including for instance the effective potential for improving efficiency, the paucity of data on crop-specific nutrient application rates, area fertilized, and corresponding yield responses, and the lack of explicit incorporation of market prices of fertilizers in any of the projection exercises (Wood et al., 2004).

Nitrogen is the major nutrient in rivers. Anthropogenic disturbance of river nutrient loads and export to coastal marine systems is a major global problem affecting water quality and biodiversity. Several studies have examined river nitrogen transport to oceans (see, for example, Seitzinger and Kroeze, 1998; Seitzinger et al., 2002; Turner et al., 2003; Van Drecht et al., 2003; Green et al., 2004). In order to estimate the nitrogen fluxes for the MA scenarios, the scenarios were related to a previous study by Bouwman et al. (2005) that uses the FAO AT2030 (FAO, 2003) results, given the firm relationships between total inputs of nitrogen in terrestrial systems (deposition, biological fixation, fertilizers, and animal manure) and the river transport of nitrogen. Results indicate further increases in nitrogen transport in rivers in the GO, AM, and OS scenarios at levels at or above 50 million tons per year by 2030; only the TG scenario shows a decrease in river nitrogen loads, as a result of less meaty diets combined with enhanced wastewater treatment, and reduced atmospheric deposition (MA, 2005c).

Box 2 – Projections of global nitrogen fertilizer use.

Projections of global nitrogen fertilizer use cover a range of time horizons, scenarios, and underlying assumptions. Bumb and Baanante (1996) generated projections of N fertilizer to 2000 and 2020 from a baseline of 79 million tons in 1990, using 3 approaches, the *Nutrient Removal Approach* and the *Cereal Production Method* to assess N requirements to meet projected cereal needs in 2020 (Rosegrant et al., 1995) and the *Effective Fertilizer Demand Method* projecting N use on the basis of a range of economic, demographic, and other factors. These 3 approaches arrived at global fertilizer N projections for 2020 of 203 million tons, 146 million tons, and 115 million tons, respectively.

Tilman et al. (2001), based on linear regressions of N fertilizer usage and time, population, and GDP for the period 1960 to 1999, extrapolated mean values of N fertilizer use of 135 million tons in 2020 and 236 million tons in 2050. Daberkow et al. (1999) built on crop area and yield projections developed by the FAO in support of the Agriculture Toward 2015/30 study (Bruinsma, 2003) to assess corresponding fertilizer needs. The authors used the *Fertilizer Use By Crop* database (IFA et al., 1999) to derive crop-specific nutrient application and response rates for 3 scenarios: *Baseline*, *Improved Nutrient Use Efficiency*, and *Nitrogen Use on Cereals.* Projected N fertilizer needs were 100 million tons, 88 million tons, and 106 million tons in 2015, and 118 million tons, 96 million tons, and 125 million tons in 2030, respectively. Galloway et al. (2004) based their N fertilizer projections to 2050 on the Daberkow et al. (1999) "baseline" scenario for 2030, and extrapolated an N fertilizer use of 135 million tons in 2050 assuming a constant N fertilizer growth rate to 2050.

Frink et al. (1999) project N fertilizer use based on producing sufficient calories (10,000 calories per person per day) for 10 billion people in 2070. Scenarios included (1) farm productivity at 1990 levels (constant nutrient use efficiency and crop yield); (2) fertilization solely through N deposition from the atmosphere, (3) modest yield growth with improved NUE, and (4) pre-1990 crop yield growth with improved NUE. These scenarios result in 284 million tons, 0 tons, 192 million tons, and 192 million tons, respectively. In the case of no N application through deposition only, crop land would have to expand to 207% of global area, i.e. this scenario is not feasible to achieve the projected calorie requirements in 2070.

Wood et al. (2004) undertook a set of N fertilizer projections based on newer fertilizer use by crop data for both a *Trend Analysis* and a *Future Food Need Scenario* (using IMPACT projections updated to 2050 for the MA Scenarios). The trend analysis was based on an update of the Bumb and Baanante (1996) *Effective Demand Approach* and assumed that N fertilizer applications would be higher in areas of significant soil degradation between 2020 and 2050 as part of a broader strategy of soil fertility restoration. Results were 112 million tons for 2020 and 171 million tons for 2050. Given the conservative assumptions about constant nitrogen use efficiency and the goal of soil rehabilitation embedded in this analysis, results likely present an upper bound on N fertilizer needs. The *Future Food Need Scenario* used 2 scenarios, the first assuming constant nitrogen use efficiency, based on the *Nitrogen Use on Cereals* approach of Daberkow et al. (1999), and the second based on the *Improved Nutrient Use Efficiency* approach of Daberkow et al. (1999), but with region-specific nitrogen use efficiencies. The projected N fertilizer consumption in 2020 and 2050 under the constant NUE assumption was 112 million tons and 121 million tons, respectively. Assuming improved NUE the corresponding quantities are 96 million tons and 107 million tons, respectively.

Sources: Wood et al. (2004); MA (2005c)

Implications for land use change, biodiversity, and hot spot areas

Increases in total demand for cereals, livestock, and fish will have large implications for the future intensity and expansion of agricultural land and the ecosystem services provided by the natural grassland and forestland that will be converted as a result. The largest expansion of agricultural land occurs in developing countries under the Order from Strength scenario because of low investments in technology and therefore slower improvements in crop yield combined with a relatively large population increase and relatively low income growth. Moreover, barriers to world food trade in this scenario imply inefficiencies in crop production. Globally, crop area is projected to increase by 137 million ha to reach 823 million ha to supply future food needs, equivalent to an annual rate of 0.34%, before slowing to 0.25% per year during 2050-2100. The rate of loss of original forests is projected to actually increase from the historic rate (of about 0.4% annually between 1970 and 2000) to 0.6% under this scenario. In the OECD region, on the other hand, agricultural land is projected to decline. Under the Global Orchestration scenario, undisturbed forests disappear at a slower rate than in Order from Strength, but still at near-current global rates. Under this scenario, about 50% of the forests in Sub-Saharan Africa will be cut down between 2000 and 2050 (MA, 2005c).

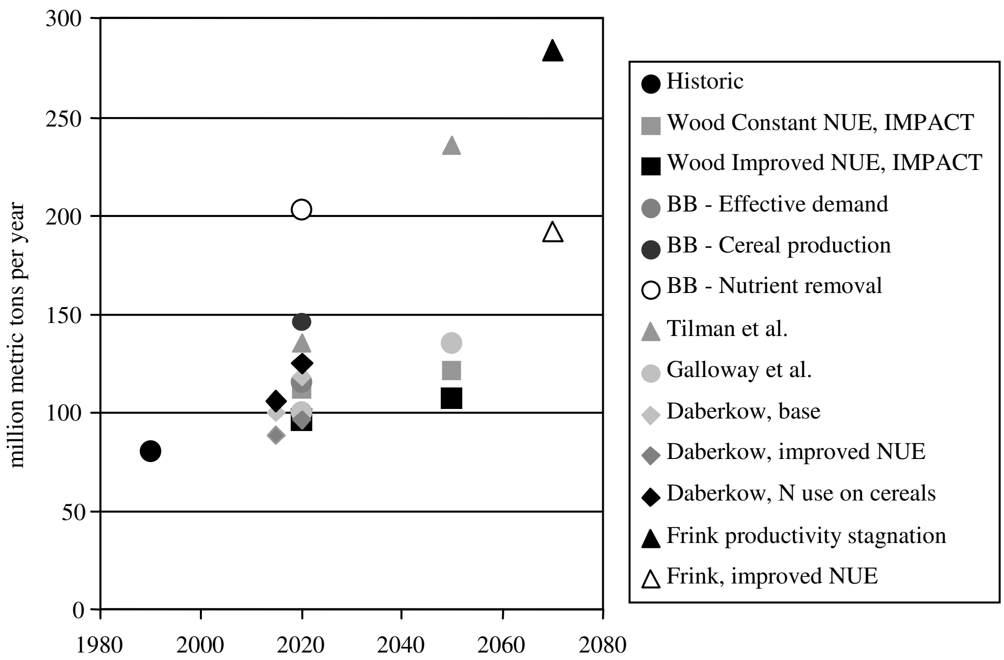


Figure 7. Projections of Fertilizer N use, various scenarios.

Worldwide, the calculated decrease of biodiversity in the 2000-2050 period compared to 1970 levels varies between 12% and 15%. By far the strongest decrease occurs under the OS scenario, which has the largest expansion of crop land due to slow yield improvement, expansion of pastures, and high population growth. In fact, by 2050 the species loss of this scenario would hardly slow down compared to historical rates. This is followed by rates of decline in the Global Orchestration scenario (MA, 2005c). Simulations suggest that 3 parts of the world in particular may undergo faster changes in ecosystem services than other regions: Central Africa, where agricultural area is set to expand at the expense of forests and grassland causing large declines in the services these biomes provide; the Middle East and North Africa, where rising incomes will lead to greater food demand and yet higher levels of food imports and further pressures on limited water resources; and South Asia, where both deforestation and water scarcity will adversely impact ecosystem services in the long run.

Other ecosystem services adversely impacting future food production levels include increased water scarcity, ecological side effects of further intensifying inputs to agriculture (fertilizer, irrigation, pesticides), and increasing levels of soil erosion. Water stress is caused through increased withdrawals for irrigation and other uses as well as rapidly increasing pollution loads. Under the Global Orchestration scenario, the areas of severe water stress expand to reach about 4.9 billion people, up from 2.3 billion people in 1995. Under the Adapting Mosaic and Order from Strength scenarios, about 5.3-5.5 billion people will live in river basins with severe water stress—some 60% of the world's population. Fossil fuel consumption resulting from economic and agricultural growth will increase particularly rapidly in the Order from Strength (by a factor of 2.5 between 2000 and 2100) and the Global Orchestration scenarios (by a factor of 2 during the same period) (MA, 2005c).

Conclusions

Over the past 50 years, people have changed ecosystems more rapidly than in any comparable time in history. These changes have helped meet rapid increases in demand for food, fiber, timber, freshwater, and fuel. While these provisioning ecosystem services increased to accommodate growing and more affluent populations, they have been achieved at a cost to many other services.

In the coming decades, ecosystem service provision, particularly for food, feed, fiber, and biofuels, will continue to increase, but adverse impact on ecosystems will also grow in magnitude. Whereas in the coming decades most adverse impacts on ecosystems will likely derive from land use change, in the longer term, impacts from climate change might likely be more decisive for ecosystem changes and adverse outcomes of ecosystem services for human well-being. Many poor people will still be food insecure by 2050, even with increased production seen under all 4 scenarios.

Importantly, the Millennium Ecosystem Scenario exercise has shown significant tradeoffs among ecosystem services, including tradeoffs among increased food security and environmental outcomes, such as biodiversity losses, increased water scarcity, and growing pollution levels. Nitrogen fertilizer is an example of tradeoffs involved in ecosystem service provision. While rapid increases in fertilizer use have helped increase national and global food security levels enormously, they have also led to significant degradation of freshwater supplies, and caused adverse human health impacts. Future research will need to work increasingly on balancing these interlinkages focusing on enhanced food security results while maintaining or improving non-food ecosystem services. Research is required particularly on land use change impacts on ecosystems and biodiversity, mitigation strategies for climate change, increasing water security, and for hot spot regions where ecosystem services and human well-being are particularly vulnerable, including Sub-Saharan Africa, South Asia, and the Middle East and North Africa region.

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