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World food markets into the 21st century: environmental and resource constraints and policies†

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Projections of global food supply and demand to the year 2020 indicate that food production in the aggregate is likely to keep pace with growing populations and incomes, and that real food prices will be stable or slowly declining. This article examines the possible environmental and resource constraints to long-term food production growth and explores the implications of these possible constraints for food and resource policies. The article reviews and synthesises the evidence on biophysical limits to crop productivity; plant genetic resources and biotechnology; the availability of plant nutrients; soil and land degradation; the increasing scarcity and declining quality of water; and the impact of global climate change on agriculture.

1. Introduction

Global food policy has been driven by the need to feed an increasing population, and to support diversified consumption patterns as incomes rise. Agricultural production growth has been able to meet these goals: in the past three decades effective demand has been met while real food prices have declined dramatically. Projections from global food supply and demand models developed at the International Food Policy Research Institute (IFPRI) (Rosegrant *et al.* 1995), the Food and Agriculture Organization (FAO) (Alexandratos 1995), and the World Bank (Mitchell and Ingco 1993) indicate that food production is likely to keep pace with growing populations and incomes, and real food prices will be stable or slowly declining over the next twenty years. However, spurred by the increasing policy priority for

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environmentally sustainable use of the natural resource base, concerns have been raised that the long-term growth rates in agricultural production projected in these global models are unsustainable (Brown 1995; Kendall and Pimentel 1994). In this article, we assess whether environmental and resource limitations are likely to threaten future global food supplies.

We first briefly summarise recent trends in crop area, yield and production, describe IFPRI's global food projections model, present an overview of food supply and demand projections using this model, and compare these projections with historical trends. The article focuses on cereals, which are the key staple crops for most of the world. We then examine possible environmental and resource constraints to long-term agricultural growth. Different sections assess the potential for expansion of cropland area and land losses due to urbanisation; biophysical limits to crop productivity; plant genetic resources and biotechnology; the future role of chemical fertiliser in agricultural growth; the economics of energy for agriculture; the impact of land degradation on crop productivity; the effect of increasing scarcity and declining quality of water; and the impact of global warming.

2. Trends in global food production

Trends in area, production and yield for cereals are summarised in table 1, for the periods 1967–82, and 1982–94. The two sub-periods roughly divide the table into a peak-Green Revolution period and a post-Green Revolution period. The pattern of growth of cereal yields shows a significant slowdown after 1982, but hardly the stagnation in yields claimed by some observers (Brown and Kane 1994; Plucknett 1995). In the developed world, the slowdown in crop area, yield and production growth was primarily policy-induced, as North American and European governments drew down cereal stocks and scaled back farm-price support programs in favour of direct payments to farmers. The economic collapse and subsequent economic reforms in the former centrally planned economies in Eastern Europe and the former Soviet Union further depressed crop production for developed countries as a whole.

The slowdown in cereal productivity growth in developing countries, and particularly in Asia, since the early 1980s, has been caused by declining world cereal prices and by factors related to the increasing intensification of cereal production. Increased intensity of land use has led to increasing input requirements in order to sustain yield gains (Rosegrant and Pingali 1994; Byerlee 1994; Morris and Byerlee 1996). Between 1982 and 1995, real world wheat prices declined by 28 per cent, rice prices by 42 per cent, and corn prices by 43 per cent (computed from World Bank 1996a). The declining

Table 1 Crop area, production and yield growth rates, 1967–1994.[a]

	1967–94			1967–82			1982–94		
	Area	Prod.	Yield	Area	Prod. (per cent per year)	Yield	Area	Prod.	Yield
Wheat									
Developed	– 0.68	0.94	1.64	– 0.12	1.73	1.87	– 1.38	– 0.03	1.35
Developing	0.99	4.29	3.27	1.45	5.39	3.88	0.42	2.94	2.52
World	0.00	2.13	2.13	0.48	2.88	2.40	– 0.59	1.20	1.80
Maize									
Developed	0.24	1.99	1.74	0.64	3.05	2.33	– 0.26	0.69	1.01
Developing	0.96	3.55	2.56	0.65	3.46	2.80	1.36	3.66	2.27
World	0.70	2.63	1.91	0.64	3.20	2.52	0.77	1.93	1.16
Paddy rice									
Developed	– 0.25	0.07	0.32	– 0.23	– 0.14	0.09	– 0.28	0.34	0.61
Developing	0.55	2.68	2.13	0.81	3.21	2.38	0.21	2.03	1.81
World	0.52	2.51	1.98	0.78	2.96	2.17	0.20	1.94	1.74
Other grains									
Developed	– 0.44	0.38	0.82	0.52	1.32	0.79	– 1.63	– 0.78	0.85
Developing	– 0.43	0.68	1.11	– 0.87	1.20	2.08	0.12	0.03	– 0.09
World	– 0.43	0.48	0.91	– 0.15	1.28	1.43	– 0.79	– 0.52	0.26

Note: [a] Based on three-year moving averages.
Source of basic data: FAO 1997.

price of cereals has caused a direct shift of land out of cereals and into more profitable cropping alternatives and has slowed the growth in input use and investment in crop research and irrigation infrastructure, with consequent effects on yield growth (Rosegrant and Pingali 1994; Rosegrant and Svendsen 1993). Perhaps the most remarkable aspect of cereal yield growth in the developing world since 1982 is not that growth was slower than in the previous period, but that growth has been as high as it was in the face of steeply declining real prices.

3. Projections of global food supply and demand

Global food projections have been made using IFPRI's global food model, the International Model for Policy Analysis of Commodities and Trade (IMPACT). IMPACT covers 37 countries and regions (which account for virtually all of the world's food production and consumption), and 17 commodities, including all cereals, roots and tubers, soybean, and meats. The model is specified as a set of country-level supply and demand equations. Each country model is linked to the rest of the world through trade. Demand is a function of prices, income and population growth. Growth in crop production in each country is determined by crop prices and the rate of productivity growth. Future productivity growth is estimated by its component sources, including management research, conventional plant breeding, wide-crossing and hybridisation breeding, and biotechnology and transgenic breeding. Other sources of growth considered include private sector agricultural research and development, agricultural extension and education, markets, infrastructure and irrigation. IMPACT is described in detail in Rosegrant *et al.* (1995). Results presented here are from a new version of IMPACT, with the base year updated from 1990 to 1993.

3.1 World food prices

The baseline projections results of the IMPACT model indicate that cereal production in the world will grow fast enough for world prices of cereals to be falling, but at a slower rate than in recent years. Cereal prices on average are projected to drop by 11 per cent by 2020. The decline in prices is accompanied by increasing world trade in food, with the developing world as a group increasing its food imports from the developed world. Net cereal imports of developing countries will more than double by 2020, reaching 228 million metric tons. In the next section, we address the underlying trends in food demand and production that produce these projections of a continued (but much slower) decline in food prices.

3.2 Food and feed demand

The most important underlying trends on the demand side are rapidly increasing urbanisation, changing tastes and preferences, and rising incomes, which are causing a shift to more diversified diets with higher per person consumption of meat, milk and milk products, fruits and vegetables, and lower per person consumption of cereals. In China and much of Southeast Asia, per person consumption of rice is already falling; and rates of growth in per person cereal consumption are declining even in South Asia. This dietary transition reduces demand pressure on basic food staples. At the same time, these trends will increase the demand for maize and coarse grains for animal feeds.

Growth rates in total food and feed demand will decline, due to both changes in the diet structure and a continued gradual slowdown in population growth. Table 2 shows the projected increase in total cereal demand between 1993 and 2020. Total cereal demand will increase by about 718 million metric tons during this period, from 1.8 billion metric tons in 1993 to 2.5 billion metric tons in 2020. More than 80 per cent of this increase

Table 2 Increase in total demand for cereals, by region, 1993–2020

	Rice	Wheat	Maize	Other grains
		(million metric tons)		
China	21.0	40.3	79.3	5.1
India	35.4	39.2	3.2	6.8
Other South Asia	15.8	27.4	2.1	0.8
Other East Asia	1.2	3.4	11.0	0.7
Southeast Asia	28.2	7.5	18.0	0.5
Sub-Saharan Africa	11.9	10.3	28.1	34.2
Latin America	7.8	12.8	40.5	9.4
West Asia and North Africa	6.5	51.2	9.9	20.9
Developed	1.5	30.5	56.1	38.6
Developing	128.0	192.4	192.3	78.3
World, total	129.5	229.9	248.4	116.9
% increase from 1993, World	36.1	40.3	47.2	34.8

Source: IMPACT simulations.

will come from the developing world, where both population and income effects are higher than in the developed economies. The almost 20 per cent share of the developed countries will be mainly in maize, and to a lesser degree in wheat and other coarse grains. China and India will jointly account for more than 30 per cent of the total cereal demand increases. The rest of Asia will account for another 16 per cent. Sub-Saharan Africa and West Asia and North Africa will each account for about 12 per cent, and Latin America for 10 per cent.

3.3 Area and yield growth

As shown in table 3, area expansion will almost cease to contribute to future production growth, with a total addition to area in cereals and roots and tubers by 2020 of only 47 million ha, from a total of 749 million ha in 1993. In Asia, crop area will increase by less than 2 per cent by 2020. Only in Sub-Saharan Africa will area expansion still be substantial; much of this increase will be in subsistence farming of roots and tubers (table 3). The projected slow growth in expansion of crop area places the burden to meet future cereal demand on crop yield growth.

Although yield growth will vary considerably by commodity and country, in general we project a decline in the rates of growth in crop yields compared to the already reduced rates of the 1982–94 period (table 4). For developing countries as a group, wheat yields are projected to grow at 1.3 per cent per year (compared to 2.5 per cent since 1982); rice yields at 1.1 per cent (compared to 1.8 per cent); and maize yields at 1.4 per cent (compared to 2.3

Table 3 Crop area harvested, cereal and root crops, by region, 1993–2020

	1993 (million hectares)	2020	Increase, 1993–2020
China	98.2	99.0	0.9
India	100.8	102.8	2.0
Other South Asia	27.1	28.0	0.9
Other East Asia	4.0	3.6	– 0.4
Southeast Asia	51.5	52.7	1.2
Sub-Saharan Africa	78.4	107.6	29.2
Latin America	51.9	58.4	6.5
West Asia and North Africa	56.4	58.3	1.9
Developed	280.1	284.7	4.6
Developing	468.6	510.8	42.2
World, total	748.6	795.5	46.8

Source: IMPACT simulations.

Table 4 Yield growth rates for various crops, by region, 1993–2020

	Rice	Wheat	Maize	Other grains
China	0.69	0.88	1.40	0.39
India	1.43	1.53	1.75	0.80
Other South Asia	1.50	1.45	1.84	0.62
Other East Asia	0.47	1.38	1.88	0.51
Southeast Asia	1.19	0.29	1.79	0.50
Sub-Saharan Africa	1.88	1.29	1.80	1.52
Latin America	1.94	1.64	1.25	0.98
West Asia and North Africa	1.81	1.70	1.39	2.20
Developed	0.53	1.06	0.84	0.78
Developing	1.08	1.30	1.36	1.24
World, total	1.05	1.17	1.03	0.85

Source: IMPACT simulations.

per cent). The one exception to this pattern is other coarse grains, which are expected to grow at 1.2 per cent per year (compared to –0.1 per cent since 1982). Rice yields in China are projected to grow at 0.7 per cent per year between 1993 and 2020, compared to the 1.8 per cent annual growth rate since 1982. For wheat, the annual yield growth rate will be 0.9 per cent, compared to the 3.0 per cent growth rate since 1982. Yield growth for rice and wheat will also slow down in India and elsewhere in South Asia relative to recent trends – but for these countries, where Green Revolution technology was exploited later, yield growth rates will remain above those in China and Southeast Asia. Some recovery is projected for cereal yield growth rates in Sub-Saharan Africa with improved political stability, increased use of inputs, and policy reform.

Can the crop area, yield and production growth rates projected here be attained? What are the possible environmental and resource base constraints to attaining the necessary production to meet rising populations and incomes? In the remaining sections, we examine these issues and discuss their implications for environmental and resource policy.

4. Cropland potential and land loss to urbanisation

In 1993, crop area harvested for cereal and root crops was 749 million ha (280 million ha in the developed world, and 469 million ha in the developing world); and, according to the IMPACT simulations, this area will increase to 796 million ha by 2020. There will be virtually no increase in crop area in developed countries, while in developing countries the area will increase to 511 million ha (table 3). Cereal and root crop area represented just over 70 per cent of total crop area in 1993.

4.1 Cropland potential

In order to obtain an estimate of the cropland potential, the entire land area which could be possibly converted to agricultural uses has to be taken into account. According to Buringh and Dudal (1987), out of 12 400 million ha of land resources, consisting of arable land, permanent pasture, forest and woodland and other land, 10 100 million ha have zero potential for growing crops, 2600 million ha have a low or medium capability for crop production, and 700 million ha have a high potential. Thus, the theoretical maximum potential suitable for crop production would be at least 3300 million ha.

However, most of the currently cultivated land constitutes relatively good agricultural land, and the productivity of other land forms converted into cropland is expected to be lower than the existing land stock. Conversion also eliminates forest and rangelands, which fulfil essential functions in their present uses. Thus, according to Kendall and Pimentel (1994), the world's arable land might be expanded at most by 500 million ha, at a productivity below present levels. The majority of potential cropland, about 87 per cent, is located in developing countries, mainly in Sub-Saharan Africa and Latin America. In Asia, on the other hand, nearly 80 per cent of the potentially arable land is already under cultivation (Plucknett 1995).

Both the theoretical maximum potential crop area and the more realistic lower potential for conversion of land resources to agricultural production are far higher than the actual IMPACT projections of increases in cropland through the year 2020. Therefore, the lack of cropland *per se* cannot be considered a major constraint to future agricultural production growth.

4.2 Land loss to urbanisation

It has been suggested that current, unprecedented increases in urban population may constitute a potential threat to agricultural production through the loss of agricultural prime land (Brown and Kane 1994). The urban population in the world is expected to increase to over 5 billion by 2025, from 1.5 billion in 1975, and 2.6 billion in 1995. This implies an overall urban growth rate of 2.3 per cent between 1995 and 2025. The majority of the population is projected to live in urban areas by 2025 (61 per cent), up from 38 per cent in 1975 and 45 per cent in 1995. Whereas more than 70 per cent of the population in both North America and Europe was living in urban areas by 1995, urbanisation accounted only for 34 and 35 per cent in Africa and Asia, respectively. Almost all urban population growth, about 90 per cent, will therefore occur in developing countries, where roughly 150 000 people are added to the urban population every day (WRI 1996). This expansion of the urban population has been estimated to result in 476 000 ha of arable land being transformed annually to urban uses in developing countries (USAID 1988). This would be equivalent to a loss of 14.2 million ha of land to urban uses between 1990 and 2020.

However, there is very little data on urban absorption of land previously under cultivation. The actual cropland loss would have to be determined considering the type of land converted into urban uses, as well as the final urban per person land area. Historically, more potential cropland has been converted to agricultural activities and grazing than urbanisation has taken away. Even assuming that the 14 million ha of land converted to urban uses came completely from crop area, this would represent a loss of only 2.6 per cent of projected cereal and root crop area in 2020. Given that 42 million ha of additional cropland could be brought under cultivation by 2010 through increases in cropping intensity on existing cropland (Alexandratos 1995), and that 500 million ha of potential cropland is available for conversion, the loss of land to urbanisation will not be a serious threat to the projected growth in crop area.

5. Physical limits to crop productivity

Global food production can increase through expansion of cropping area and increases in cropping intensity (see above), or through increases in agricultural productivity. Although there is ample margin to expand agricultural area, overall crop area, as shown in the IMPACT simulations, is expected to grow only slowly due mainly to projected declining world food prices. Thus, increases in agricultural productivity will have to bear the brunt of achieving the necessary production rates to meet global food demand.

The Green Revolution, with the introduction and successful adoption of high-yielding varieties of wheat and rice, the development and application of chemical fertilisers and other agricultural chemicals, accompanied by investments in institutional infrastructure and irrigation, substantially increased agricultural output in the 1960s and up to the 1980s; recently, however, it has been suggested that rice and wheat yields have reached a yield plateau, and from Asia it has been reported that some areas experience production pressures under increasing intensification and might face declining factor productivity (Plucknett 1995; Brown and Kane 1994).

Facing all these challenges, will agricultural productivity as the main engine of agricultural production growth be able to keep up with global food needs, or are the biophysical yield limits already within reach? Are the projected yield growth rates up to 2020 achievable? The earth's biophysical limit of food production is reached when all land suitable for agriculture is cropped and irrigated, and the potential yield on each field is attained and the remaining suitable grazing land is grazed. There is a specific upper limit to crop yield on any given piece of land, which is determined by soil type, climate, crop properties, and available irrigation water; it is reached when the farmer selects the optimal combination of crop species and management practices (Penning de Vries *et al.* 1995).

Maximum theoretical yields are calculated for specific crops as the highest limit of biological potential for a given location on the basis of photosynthetic potential, land quality, length of the growing season, and water availability. Maximum theoretical yields in grain equivalents (with rice in milled form) were calculated by Linneman *et al.* in 1979. Biophysical limits vary from one region to another due to different underlying conditions in the agricultural sectors. Whereas South America has a huge potential for increasing agricultural production, with an estimated maximum production of 18 tons per ha per year, the limits are lower for Africa (14 tons per ha), Asia (13 tons per ha), North and Central America (11 tons per ha), and Europe and Australia (10 tons per ha). These numbers indicate a wide margin between actual yields (between 0.7 and 3.8 tons per ha per season, on average, in 1990–92) and theoretical maximum yields. Projected yields in 2020 are all well below the maximum theoretical yields. Thus, despite the slowdown in yield growth over the past fifteen years, overall yield trends by country and region indicate ample room for yield improvement in most crops and regions (Plucknett 1995). Existing wide disparities in yields among countries in the same region and between continents also give rise to the expectation that considerable improvements in agricultural productivity could be achieved.

However, in order to maintain yield growth and to further increase the yield potential, agricultural research at several levels will be essential:

productivity maintenance research in order to keep yield increases up; research to maximise yields through improved and extended resistance to biotic and abiotic plant stresses; research towards closing the yield gaps between farm yields and practical farm and research station yields, and strategic research towards raising the yield ceilings (Plucknett 1995).

6. Plant genetic resources

Can the plant genetic base sustain further growth in food crop yields and thus hold the promise given by physical limits to crop productivity? Genetic resources can be conserved *ex situ* (not in the original or natural environment), or *in situ* (where naturally recurring). *Ex situ* strategies preserve plant seeds and propagating parts in gene banks, preventing the loss of species and subspecies. *In situ* conservation allows observation of the evolution of species as they interact with pests and pathogens (Smale and McBride 1996).

In situ conservation of genetic resources may be an important complement to *ex situ* conservation because it allows adaptive and evolutionary processes to continue, and may provide as yet unknown genetic characteristics for future breeding (Wright 1996; Smale and McBride 1996). However, for the foreseeable future, crop yield increases will rely on germplasm drawn from breeding lines stored *ex situ* (Wright 1996; Evenson and Gollin 1994). Global *ex situ* storage of germplasm is substantial for the major food crops. Approximately 75 to 90 per cent of the estimated genetic variation in the major crops and about 50 per cent for minor crops is found in gene banks (Wilkes 1992). Concerns, however, have been expressed about the availability of information on sources, propagation techniques, basic characteristics, and the quality of some of the germplasm held in gene banks (McNeely *et al.* 1990). Nevertheless, if funding is sustained for proper documentation, evaluation and maintenance of the existing system of germplasm banks, the availability of germplasm appears sufficient to sustain future breeding efforts to support the crop yield growth rates projected above.

6.1 Crop genetic diversity

Although the available germplasm is characterised by wide genetic variation, the number of varieties actually tapped and utilised to develop new varieties is relatively small at any given point in time. This practice has led to the criticism that the development of modern rice and wheat varieties has narrowed the genetic base in farmers' fields, thereby increasing the threat of disastrous yield declines if, for example, genetic resistance to an insect or disease breaks down. However, this criticism is based on a narrow understanding of genetic diversity in terms of spatial or cross-sectional diversity. Moreover, for wheat, even spatial diversity (measured as the concentration of leading varieties in farmers' fields at a given point in time), is increasing over time, and is greater now than in the early twentieth century (Smale 1996; Smale and McBride 1996). For rice, spatial diversity may have narrowed following the introduction of modern varieties in the 1960s. However, spatial diversity is only one measure of genetic diversity, and other important measures have improved over time for rice (and wheat): temporal diversity (average age and rate of replacement of cultivars); polygenic diversity (the pyramiding of multiple genes for resistance to provide longer-lasting protection for pathogens); and pedigree complexity (the number of landraces, pureline selections, and mutants that are ancestors of a released variety) (Evenson and Gollin 1994; Smale 1996). Genetic diversity is multi-dimensional, difficult and expensive to measure, and extraordinarily complex. Nevertheless, trends in genetic diversity of cereal crops are mainly positive, with diversity generated primarily as a byproduct to breeding for yield and quality improvement.

7. Biotechnology

The key to tapping the potential represented by the available genetic resources (and to increasing genetic diversity) will increasingly be the application of biotechnology in tandem with conventional plant breeding. Biotechnology for agriculture includes (a) agricultural microbiology; (b) cell and tissue culture for rapid propagation of plant species and facilitation of wide crosses between different species; (c) new diagnostics methods using monoclonal antibodies or nucleic acid probes to identify diseases and viruses; (d) genetic mapping techniques for faster identification of useful genetic material to make conventional plant breeding more efficient; and (e) genetic engineering to incorporate 'alien' or novel genes into plant species (Persley 1994; Leisinger 1995). Unlike conventional breeding, genetic engineering can create 'transgenic' crops, that include genetic material that would otherwise never or only in extremely rare cases belong to a certain species (de Kathen 1996).

The benefits of biotechnology include the introduction of higher plant resistance to pests and diseases; the development of tolerance to adverse weather conditions; the improvement in nutritional value of some foods; and ultimately the increase in the genetic yield potential of plants. The main successes of biotechnology thus far have been in improved pest and disease resistance, increasing yields through reduction in yield losses and extension of potential areas for production of high-yielding crops, rather than direct increases in crop yield potential. A recent survey of releases of transgenic plants in developing countries identified 159 releases, nearly one-half of which conveyed herbicide resistance, one-third provided insect resistance, and the remainder virus resistance, product quality and other improvements (de Kathen 1996).

The International Agricultural Research Centers (IARCs), after a relatively slow start, have been increasing their research in crop-related modern biotechnology; and over the 1985–95 period, about US $260 million have been provided for international agricultural biotechnology programs, including US $206 million for 25 international agricultural research programs and about US $7 million for four international biotechnology networks (Cohen 1994). Biotechnology research is currently dominated by the private sector in developed countries: it is estimated that some US $900 million was spent on agricultural biotechnology research and development in 1985, of which US $800 million was spent in developed countries and US $550 million by the private sector (Livernash 1996).

The small share of developing countries in biotechnology research is partly due to time-lags caused by the development of a complex and expensive technology that originated in the developed world. But it is also a function of what appears to have been a conscious decision on the part of developing country research centres and the IARCs to 'go slow' on biotechnology, because of the perception (a) that biotechnology research had not yet reached the state of 'tool development' where large expenditures would be justified; (b) that biotechnology research in the modern era of intellectual property rights is inherently a private sector activity; and (c) that the support system for the IARCs and National Agricultural Research Institutes (NARs) is oriented towards the development of technology, not upstream science (Evenson and Rosegrant 1993). Although all three justifications have some validity, it will be crucial to increase biotechnology research aimed at the situations prevalent in developing countries, in order to give these countries access to the next-generation yield potentials; as compared to most current agricultural biotechnology research undertaken in developed countries, which is aimed at plants suitable for temperate climates (Livernash 1996).

Fortunately, new institutional arrangements between developed and developing countries have been put in place recently, and some developing countries, like China or India, have increased their annual budgets for their research institutes. The IARCs could play an essential role in developing local biotechnology capacity, sharing information across countries, and collaborating with private-sector partners (Livernash 1996). This process would be greatly facilitated by the removal of unnecessary barriers to the free movement of plant materials, clarification of biosafety regulations, and provision of improved property rights protection for new products

(Yudelman 1996). If funding and collaboration efforts between international centres continue to grow, biotechnology will provide a significant boost to crop production in the next century.

8. Fertiliser

Can continued expansion of fertiliser use support the projected gains in crop yields without damaging the environment? Global fertiliser use (in nutrient terms) increased from 27 million tons in 1960 to 146 million tons in 1989 and decreased thereafter to 121 million tons in 1994. This drop in global fertiliser use is primarily the result of steep declines in fertiliser application in the reforming economies of Eastern Europe and the former Soviet Union (Bumb and Baanante 1996). The developing countries' share of global fertiliser use increased to 58 per cent in 1995, compared to 10 per cent in 1960 and 31 per cent in 1980 (Bumb and Baanante 1996).

With long-term high growth rates in fertiliser use and declining growth rates in yield, fertiliser levels in relatively favourable areas of Asia are now quite high, and increasing amounts of fertiliser are being used to maintain current yield levels. In parts of Asia, including West Java in Indonesia, the Indian Punjab, and parts of China, fertilisers are being used at or above economically optimum levels at border prices. In East Asia, average fertiliser use is nearly 220 kilograms per hectare. In much of this region, further increases in fertiliser application will be small, but there is considerable room for improvement in fertiliser use efficiency, nutrient uptake rates, and nutrient balance (Rosegrant and Pingali 1994). In most of the rest of the developing world there remains substantial scope for increasing crop yields through increased fertiliser use. In South Asia, for example, fertiliser use is only about 80 kilograms per hectare; in Latin America, 65 kilograms per hectare; and in Sub-Saharan Africa, only about 20 kilograms per hectare (Bumb and Baanante 1996).

8.1 Future growth in fertiliser demand and supply

Bumb and Baanante (1996) estimated effective demand growth for fertiliser, taking into account foreign exchange availability, exchange rate, crop and fertiliser prices, the development of irrigation and other infrastructure, and the impact of policy reforms on fertiliser demand. During the 1990–2020 period, global fertiliser demand is projected to increase 1.2 per cent per year. In absolute amounts, fertiliser use is projected to increase from about 144 million tons in 1990 to 208 million tons in 2020. Developed countries are expected to show virtually no growth in fertiliser use, with a slow growth in North America and a slow recovery in Eastern Europe and the former Soviet

Union balanced by a decline in Western Europe. Fertiliser use in developing countries is projected to grow at 2.2 per cent per year. While these fertiliser demand growth rates are relatively low, they are certainly adequate to support the projected yield growth rates shown above.

Can the production of fertiliser keep up with the projected effective demand? The projections of supply potential developed by the World Bank/ FAO/UNIDO Industry Fertilizer Working Group (1994) and IFDC (Bumb 1995) suggest that the world will have the capacity to produce between 147 and 163 million tons of fertiliser nutrients in the year 2000. In order to meet the projected effective demand in 2020, an additional 55 to 71 million tons of nutrients will have to be produced. Assuming the lower capacity figure for 2000, fertiliser production should be increased at an annual rate of 1.4 per cent during the 2000–20 period to satisfy the projected effective fertiliser demand. Given the 5.7 per cent annual growth in fertiliser production during the 1960–90 period, reaching this required growth should not be difficult. Bumb and Baanante (1996) also show that raw materials are not likely to be a constraint on meeting future global fertiliser demand.

The one constraint that could slow the expansion of fertiliser capacity is continued low fertiliser prices. The real price of urea in 1993 was only one-third of its 1980 price, before beginning to recover, and in 1995 was still only 60 per cent of the 1980 value. The 1995 prices of diammonium phospate, phosphate rock, potassium chloride, and TSP were also in the range of 50 to 60 per cent of their 1980 values. World Bank (1996b) projections indicate that fertiliser prices will be stable or slightly lower through 2005. If these price levels constrain future investment in fertiliser production capacity, fertiliser prices could increase in later years; this would induce a reduction in growth in fertiliser use, combined with improved efficiency of fertiliser use, with possibly negative effects on crop yield growth. However, an alternative simulation with the IMPACT model shows that, even assuming no efficiency gains in fertiliser use, a 50 per cent increase in real fertiliser prices (much higher than likely increases) would reduce crop yields in 2020 by only about 2 per cent in absolute terms.

8.2 Fertiliser and the environment

Are the projected rates of growth in fertiliser use a threat to the environment? The two major environmental effects of high levels of fertiliser use are nitrate leaching or runoff and eutrophication. Nitrates can leach from the soil or run off in drainage water when the supply of nitrogen from fertiliser and other sources exceeds nitrogen uptake by plants. Eutrophication occurs when fertiliser is carried by soil erosion and water runoff to lakes, rivers, or other water bodies, potentially causing excess growth of algae, oxygen depletion, and fish mortality. These side effects are of considerable concern in Western Europe and parts of North America, and policies are being put in place to selectively reduce fertiliser use (Leuck *et al.* 1995). However, with the possible exception of intensively cultivated areas of East Asia and pockets of high fertiliser use elsewhere, fertiliser use in developing countries is so low that nitrate leaching and eutrophication do not pose a significant problem. In the intensively fertilised regions, soil fertility constraints will require improved management and balance of fertiliser applications.

In many developing regions, and notably in Sub-Saharan Africa, it is not overuse of fertiliser, but insufficient use that causes harm to the environment. Inadequate replenishment of removed nutrients and organic matter reduce soil fertility and increase erosion rates. Increased fertiliser use, along with other complementary measures, can help reverse environmental degradation by providing much-needed nutrients to the soil, thereby increasing crop yields and food production. Higher crop yields mean more biomass to be ploughed back to maintain the supply of organic matter and vegetative cover, thus enhancing moisture retention, nutrient use efficiency and soil productivity (Bumb and Baanante 1996).

9. Energy and agriculture

Direct (farm machinery, animal and human labour) and indirect (manufacture of agricultural chemicals, farm machinery and irrigation) forms of energy have been essential factors in bringing about increases in agricultural productivity. In the context of the Green Revolution, energy-intensiveness of agricultural production increased in some cases 100-fold or more (but from a near-zero base), and plant breeding was aimed at designing plants that could cope with high levels of fertiliser use (Kendall and Pimentel 1994). In developed countries, manufacture and farm machinery operation account for the largest but declining share of commercial energy uses in agricultural production (52 per cent in 1982), followed by chemical fertilisers with an increasing share (44 per cent in 1982). In developing countries, however, fertilisers take the first place with 69 per cent of energy share in 1982 (Bhatia and Malik 1995).

Despite increases in energy intensity in agriculture, agricultural uses of energy account for only a small fraction of total energy consumption. In 1990, only about 2 per cent of global energy consumption was required to produce fertiliser, the most energy-intensive agricultural input. By 2020, energy use in the fertiliser sector is expected to decrease to about 1.6 per cent of total energy consumption. This is partly due to increasing energy efficiency in fertiliser plants, which has improved considerably after the energy crisis of the 1970s. The globalisation and privatisation of fertiliser markets, as well as the removal of energy subsidies and inefficient organisational structures, present further possibilities to increase energy efficiency (Bumb and Baanante 1996).

Furthermore, overall energy use in agriculture constitutes only a small part of agricultural production costs. During the last 20 years, direct farm expenses for fuels, oils, and electricity have varied between 3.5 and 7.4 per cent of total farm production expenses in the United States. Together with expenditures for pesticides and fertilisers, the cost share was between 11.2 and 17.2 per cent of total farm production expenses. A study on the effects of large energy price changes on the agricultural sectors of different regions concluded that even very large and sustained increases in energy prices only lead to small declines in agricultural output and land prices, even in the very energy-intensive United States (McDonald *et al.* 1991).

Although overall energy use has been increasing during the last decades, there is some evidence that energy intensity has been decreasing in developed countries. Bonny (1993) showed a downward trend of direct energy use in overall French agriculture since the 1970s, as well as a 30 per cent drop in direct and indirect energy intensity in the production of one ton of wheat in a region in France between 1955–60 and 1990. Finally, energy prices are projected to decrease for the next decades: according to the World Bank (1996b), crude oil prices are expected to fall from US \$51.22 per barrel in 1980 (constant 1990 dollars) to US \$13.23 per barrel by 2005.

Energy use has clearly been an essential factor bringing about the Green Revolution in the 1960s, and will remain essential for achieving food security in the coming decades. However, with the prospects of increasing energy efficiency, lower energy prices, and in the context of agriculture using only a small proportion of overall energy, energy availability cannot be considered a serious resource constraint to long-term agricultural growth.

10. Land degradation

Degradation of agricultural lands is a problem in many parts of the world, with some areas under severe risk. Kasperson *et al.* (1996) identify nine ‘regions at risk’, defined as areas in which human-induced changes threaten the basic environmental structure and function which, in turn, endanger human well-being. Scherr and Yadav (1996) point to ‘hot spots’ where land degradation poses a significant threat to food security for large numbers of poor people, to local economic activity, and to important environmental products and services.

However, while these areas have severe problems that need to be addressed, these problems are in many cases localised, and will have little impact on global food production. Available estimates of the scope and severity of land degradation on a global basis, and the impact of this degradation on food production indicate that land degradation at existing rates is not a serious threat to global food security.

The most comprehensive assessment of global land degradation, Oldeman *et al.* (1990), classifies the main types of land degradation as soil erosion from wind and water, chemical degradation (loss of nutrients, soil salinisation, urban-industrial pollution, and acidification), and physical degradation (compaction, waterlogging, and subsidence of organic soils). Oldeman *et al.* (1990) mapped a total land base of 13 013 million ha, of which 4048 million ha was forest and woodland, 3212 million ha was permanent pasture, and 1475 million ha was agricultural land. An estimated 1964 million ha of land within the latter three categories has suffered from some degree of degradation. Water erosion accounts for 56 per cent of land degradation, wind erosion for 28 per cent, chemical degradation for 12 per cent and physical degradation for 4 per cent. However, for agricultural land, chemical degradation is much more important, accounting for 40 per cent of the estimated 562 million ha of degraded agricultural land (Oldeman *et al.* 1990). Of the total degraded area, 84 per cent is classified as having a 'light' or 'moderate' degree of degradation, while 'strongly' or 'extremely' degraded land accounts for 15 per cent of the degraded area.

10.1 Land degradation and crop productivity

The most important potential agricultural impact of land degradation is reduction in crop yields. Degradation may also reduce total factor productivity by requiring the use of higher input levels to maintain yields; may cause temporary or permanent abandonment of plots; or lead to the conversion of land to lower-valued uses. As noted above, estimates of the crop production impacts of land degradation are rare. Comprehensive country-level studies have only been undertaken for the United States (Alt *et al.* 1989; Crosson 1986; Pierce *et al.* 1984). These studies found very small long-term yield effects due to soil erosion: if erosion rates continued at the same rate as in 1982 for 100 years, national average yields would be 3–10 per cent lower than in the absence of erosion (Crosson and Anderson 1992).

Crop yield losses due to past erosion in Africa were estimated by Lal (1995), based on existing quantitative data on erosion rates and productivity relationships. Cumulative crop yield reductions due to past erosion were estimated to range from 2 per cent to 40 per cent across countries, with a mean of 8.2 per cent for the continent and 6.2 per cent for Sub-Saharan Africa (Scherr and Yadav 1996). National estimates of the crop productivity effects of land degradation are summarised by Scherr and Yadav (1996) for more than a dozen developing countries. Seven African countries with fairly comparable data show rates of 0.04 per cent to 11 per cent annual losses in production. These national level estimates of adverse crop yield impacts of land degradation confirm that degradation can be devastating in some countries and in fragile environments within sub-regions of countries. However, degradation rates at the national level do not in general imply a threat to global food production. Furthermore, even the relatively small estimated cumulative yield losses may considerably overstate the net impact of soil erosion. Eroded soil is often not lost to agricultural production, but rather deposited elsewhere on productive cropland or pasture (Crosson and Anderson 1992). Thus, in many cases soil erosion is a redistribution of crop production rather than a production loss.

The only attempt to develop a global estimate of the impact of land degradation on crop yields was undertaken by Crosson (1995), utilising the Oldeman *et al.* (1990) database, as well as a complementary analysis of dryland degradation by Dregne and Chou (1992). The estimated cumulative crop productivity loss due to land degradation for the period 1945–90 was about 5 per cent. This is equivalent to an annual rate of decline of 0.11 per cent over the period. While this is not an insignificant loss, the impact of degradation was dwarfed by wheat yield growth of 2.1 per cent per year during 1967–94.

Land degradation is of overriding importance in some geographic regions, but unless rates of degradation accelerate dramatically, it is unlikely that land degradation will be a serious threat to global food supply. Policies to counteract degradation should be targeted towards high risk zones. In these zones, significant public investments in research, technology development, extension services, and rural infrastructure may be necessary to stabilise or reverse degradation. More broadly, land degradation can also be mitigated through policy reforms, such as the establishment of property rights to land, market and price reforms, and the elimination of subsidies to agricultural inputs.

11. Irrigation and water resources

The resource base that may pose the most serious threat to future global food supplies is water. Irrigated area accounts for nearly two-thirds of world rice and wheat production, so growth in irrigated output per unit of land and water is essential to feed growing populations. However, development of irrigation and water supplies is increasingly expensive, limiting the potential for further expansion of irrigated area and new water supplies. In India and Indonesia, for example, the real costs of new irrigation have more than doubled since the late 1960s and early 1970s; in the Philippines, costs have increased by more than 50 per cent; in Sri Lanka, they have tripled; and in Thailand they have increased by 40 per cent (Rosegrant and Svendsen 1993). The result of these increases in costs (and declining cereal prices) are low rates of return for new irrigation construction. Reduced rates of return to new irrigation, coupled with rising environmental concerns, have in turn greatly slowed the rate of expansion of irrigated areas. Expansion of water supplies for non-agricultural purposes is also constrained by rising costs. In many developing countries, new water supplies cost three to four times more than existing water sources (World Bank 1993).

The high cost of new development puts increased pressure on existing water sources. In many regions, groundwater is being depleted, as pumping rates exceed the rate of natural recharge. While mining of both renewable and non-renewable water resources can be an optimal economic strategy, it is clear that groundwater overdrafting is excessive in many instances. In the United States, the equivalent of 4 million ha, one-fifth of the irrigated area, is watered by pumping in excess of groundwater recharge (Postel 1993). In parts of the North China Plain, groundwater levels are falling by as much as one metre per year, and heavy pumping in portions of the southern Indian state of Tamil Nadu have been estimated to reduce water levels by as much as 25–30 metres in a decade.

Non-traditional sources of water are unlikely to be a major component of new water supplies. Desalination offers an infinite supply of freshwater, but at a high price, and will not be a significant factor in most regions. The re-use of wastewater will similarly make an important contribution only in arid regions such as the Middle East where the cost of new water supplies is very high. Water harvesting (the capture and diversion of rainfall or floodwater to fields to irrigate crops) will be important in some local and regional ecosytems, but will not have a significant impact on global food production and water scarcity (Rosegrant 1995; Rosegrant and Meinzen-Dick 1996).

Because of the constraints on the development of new water sources, the rapidly growing household and industrial demand for water will need to be met increasingly from water savings from irrigated agriculture, which generally accounts for 80 per cent of water diversions in developing countries. A particularly difficult challenge will be to improve the efficiency of agricultural water use to maintain crop yields and output growth while at the same time allowing reallocation of water from agriculture to rapidly growing urban and industrial uses.

To meet this challenge, it is necessary to generate physical savings of water and economic savings by increasing crop output per unit of evaporative loss of water; increasing the utilisation of water before it is lost to water sinks; and by reducing salinisation and other water pollution that diminishes crop yield per unit of water. It is unclear how large each of these potential water savings is. Water use efficiency in irrigation in much of the developing world is typically in the range of 25 to 40 per cent, while in urban supply systems, 'unaccounted for water', much of which is direct water losses to the oceans, is often 50 per cent or more in major metropolitan areas in developing countries (Rosegrant and Shetty 1994; Rosegrant 1995). These inefficiencies seem to imply the potential for huge savings from existing uses of water. However, the potential savings of water in many river basins are not as dramatic, nor as easy to achieve as implied by these efficiency figures, because much of the water 'lost' from irrigation systems is re-used elsewhere (Seckler 1996). In these basins, efficiency gains from existing systems may prove to be limited, because whole-basin water use efficiencies are quite high due to re-use and recycling of drainage water, even though individual water users are inefficient. For example, estimates of overall water use efficiencies for individual irrigation systems in the Nile Basin are as low as 30 per cent, but the overall efficiency for the entire Nile river basin is estimated at 80 per cent (Keller 1992).

Important research remains to be done on this issue. Definitive estimates of the potential for improving crop yields per unit of water applied, and the potential for maintaining crop productivity growth while transferring water out of agriculture requires basin-specific analysis, with aggregation to the global level to assess the likely effects on food security. Can significant real water savings be achieved through improved water management policies? What would be the impact on food production and food security of transfers of saved water out of agriculture? Understanding the contributions of water management, and investment policies to future food security would provide important guidance to national and international policy-makers, and could generate large benefits for food producers and consumers in developing countries.

11.1 Implications for policy and investment

Although important questions must still be answered, a clear place to start in seeking water savings, improving water use efficiency, and boosting crop output per unit of water is through the reform of existing water policies that have contributed to the current predicament: both urban and rural water users are provided with massive subsidies on water use; irrigation water is essentially unpriced; in urban areas the price of water does not cover the cost of delivery; and capital investment decisions in all sectors are divorced from management of the resource.

These water-wasting policies can be attacked through comprehensive reforms to improve the incentives at each level of the water allocation process. Reform of the institutional and legal environment must empower water users to make their own decisions regarding the use of the resource, while at the same time providing a structure that reveals the real scarcity value of water. In addition, some of the increasing demand for water must be met from economically efficient development of new water, both through impoundment of surface water and sustainable exploitation of groundwater resources, and through expansion in the development of non-traditional water sources. Future construction of irrigation and water supply projects will require balanced development approaches acceptable to diverse constituencies. The full social, economic and environmental costs of development must be considered, but so must the economic and environmental costs of failure to develop new water sources. Failure to address the increasing scarcity of water could significantly slow the growth in crop production.

12. Climate change

According to many studies, in the coming decades, global agriculture faces the prospect of a changing climate, which might adversely affect the goal of meeting global food needs. The prospective climate change consists of global warming and associated changes in hydrological regimes and other climatic variables, such as higher temperatures, shorter growing seasons, changing moisture regimes and extreme weather patterns, as well as secondary effects on social and economic systems, induced by increasing concentrations of greenhouse gases from human activities, especially carbon dioxide (CO_2), which is projected to double by the year 2100 with an expected temperature rise in the range of 1.5–4.5°C (Wolfe 1996; Downing 1993; Kendall and Pimentel 1994).

Global warming could have both negative and positive impacts on agriculture. A 1°C increase in mean annual temperature may advance the thermal limits of cereal cropping in the mid-latitude Northern Hemisphere by 150–200 km (Schimmelpfenning *et al.* 1996). At higher latitudes, increased temperatures can lengthen the growing season and ameliorate cold temperature effects on growth. In warmer mid-latitude environments, adverse effects of climate change include increased pests and disease on crops and livestock, soil erosion and desertification due to more intense rainfall and prolonged dry periods, as well as reduced water resources for irrigation (Downing 1993). Despite the many studies on global warming since the 1980s, however, there is no consensus on the impacts of three major variables on agriculture: the magnitude of regional changes in temperature and precipitation, the magnitude of the beneficial effects of higher CO_2 on crop yields, and the ability of farmers to adapt to climate changes (Wolfe 1996).

Sensitivity studies of world agriculture to potential climate changes have indicated that global warming may have only a small overall impact on world food production because reduced production and yields in some areas are offset by increases in others. However, tropical regions may suffer negative impacts from droughts, due to the nonlinear relationship between temperature and evapotranspiration, even though climate changes in these regions are expected to be less; these regions will also face greater difficulties in shifting planting dates, as they are limited more by rainfall than temperature (Reilly 1995). Although results vary by climate change scenario and by study, regions critically vulnerable in terms of resources to support their populations and projected decreases in soil water include parts of the semi-arid tropics and sub-tropics, such as western Arabia, southern Africa, or eastern Brazil, and some humid tropical and equatorial regions, like Southeast Asia and Central America (Downing 1993). Most studies also conclude that changes will benefit Japan and China.

Moderate global warming can have positive impacts on crop yields. Most plants growing in experimental environments with enhanced CO_2 levels exhibit a 'CO_2 fertilisation' effect that increases crop yields. Under experimental conditions, for rice, wheat, and over 90 per cent of the world's plant species, the estimated effect from a doubling of CO_2 is a 30 per cent yield increase. For maize, millet, sorghum, and sugar cane, the effect is a much lower 7 per cent yield increase (Schimmelpfennig *et al.* 1996). Under field conditions, with CO_2-stimulated weeds, potential lack of water and other nutrients, estimated yield increases are estimated to be only one-quarter to one-third of the effect under experimental conditions (Kendall and Pimentel 1994).

In order to assess the potential impact of climate change on agriculture and food supply, complex climate, crop growth, and economic-food trade models have been linked. Between 1989 and 1992, a comprehensive study of alternative scenarios for the direct effects of greenhouse gas-induced climate changes on crop yields (wheat, rice, maize and soybean) was conducted at 112 sites in 18 countries with the help of crop growth models. According to this study, with a continuation of current trends in economic growth rates, partial trade liberalisation, and medium population growth rates, assuming modest farm-level adaptations to climate change, and without the CO_2 fertilisation effect, the net impact of climate change would be an estimated reduction in global cereal production of up to 5 per cent by 2060. This global reduction could be largely overcome by major forms of adaptation such as installation of irrigation. The climate change would increase the disparities between developing and developed countries with production in the developed world possibly benefiting from climate change whereas production in developing nations may decline. Under scenarios that simulate more aggressive economic and farm level adaptations to changing climate, and with CO_2 fertilisation effect, negative global cereal yield impacts are nearly eliminated (with estimated yield changes in the range of +1.0 per cent and −2.5 per cent) and only persist in developing countries (Rosenzweig *et al.* 1993).

More recent studies conclude that the negative effects of climate change on agriculture likely have been overestimated by studies that do not take into account broader economic and environmental implications or account for economic adjustments. Utilising a modelling approach capturing some of these adjustment processes, Darwin *et al.* (1995) conclude that global changes in temperature and precipitation patterns are not likely to endanger food production for the world as a whole; that farmer adaptations are the main mechanisms for keeping up world food production under global climate change; that costs and benefits of global climate change are not equally distributed around the world; and that, although water supplies are likely to increase as a whole under climate change, regional and local water shortages could occur. The impact on crop yields is generally more positive: world cereal production increases by between +0.9 and 1.2 per cent, even without CO_2 fertilisation effect (Darwin *et al.* 1995).

Prospective global temperature increases will occur gradually and not until far into the next century, and crop yield reductions and economic losses due to global warming are manageable (and perhaps positive over the next few decades). Thus, global warming will have little or no impact on global food production through the year 2020.

13. Conclusions

In this article, projections of future global food supply, based on the IMPACT model developed by IFPRI, were confronted with possible future limitations of physical and environmental resources, including plant genetic resources, fertiliser, land, water, energy, and climate. The broad conclusion is that environmental and resource constraints are not intrinsically limiting to the necessary growth in crop production to meet global food demand in the coming decades.

The case of water shows under what circumstances resources may become limiting: when agricultural and environmental problems are combined with bad policy. Of the possible limiting factors discussed here, water scarcity and pollution may be the most serious threats to the attainment of the necessary growth in food production. Development of new water sources has become increasingly expensive and irrigation water will increasingly be diverted to meet urban and industrial needs. To meet production needs, it will be necessary to generate both physical savings of water and economic savings by increasing crop output per unit of water. In order to achieve water savings, reforms of existing water policies that have contributed to the current predicament are crucial. Key elements of these reforms include establishment of secure water rights to users; decentralisation and privatisation of water management functions; and utilisation of incentives for water conservation, including markets in tradable water rights, pricing reform and reduction in subsidies, and effluent or pollution charges.

Generalising from the water context, the set of policies that are necessary to encourage food production growth while protecting the environment is quite consistent across the resource issues that were reviewed here. In the broadest sense, these are policies to improve the flexibility of resource allocation in agriculture: removal of subsidies and taxes that distort incentives; establishment of secure property rights; investment in research, education and training, and public infrastructure; better integration of international commodity markets; and a greater inclusion of populations in developing countries into these markets.

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