Environmental and Resource Policies: Implications for Global Food Markets

Mark W. Rosegrant and Claudia Ringler

International Food Policy Research Institute

January 1997

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 IFPRI (Rosegrant, et al. 1995), 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 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 paper, we assess whether environmental and resource constraints are likely to threaten future global food supplies.

We first briefly summarize 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 paper focuses primarily 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. The paper assesses the potential for expansion of cropland area and land losses due to urbanization; bio-physical limits to crop productivity; plant genetic resources and biotechnology; the future role of chemical fertilizer 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. Finally, the paper explores the implications of these potential constraints for environmental and resource policies.

Trends in Global Food Production

Trends in area, production, and yield for wheat, maize, and rice are summarized in Table 1, for the periods 1966-95, 1966-82, and 1982-95. The two sub-periods roughly divide the period into a peak-Green Revolution period and a post-Green Revolution period, although it must be stressed that the pattern of adoption of modern rice and wheat technology varied widely from country to country. 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 developing countries, wheat yield growth declined from 3.8 percent per year in the first sub-period to 2.3 percent in the second, while in the world as a whole, wheat yield growth slowed from an annual rate of 2.6 percent to 1.6 percent. Maize yield growth in developing countries dropped from 2.8 percent annual in 1966-82 to 2.0 percent thereafter. Globally, maize yield growth declined from 2.5 percent per year to 1.2 percent. Developing country rice yield growth was 2.4 percent per year in 1966-82, and 1.6 percent per year in 1982-95. Global rice yield growth dropped from 2.2 percent per year to 1.6 percent.

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 favor 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 process of intensification of cereal production. The long-term decline in the world rice price has resulted in reduced investments for irrigation infrastructure and rice research. At the same time, increased intensity of land use has led to increasing input requirements in order to sustain current yield gains (Rosegrant and Pingali 1994; Byerlee 1994; Morris and Byerlee 1996).

Much attention has been focused on the technological reasons for the slowdown in yield growth. The use of high levels of inputs and achievement of relatively high cereal yields in parts of Asia have made it more difficult to sustain the same rate of yield gains, as farmer yields in these regions approach the economic optimum yield levels. In addition, at least for rice, maximum yields on experiment stations have been flat, due to micro processes of degradation of the paddy environment related to the intensification of production (Pingali 1994), although recent developments in rice breeding and soil management at IRRI appear likely to soon push out the experiment station yield (Cassman 1994; Cassman and Harwood 1995).

Less attention has been paid to the crucial role of cereal prices in the drop in yield and production growth rates. Between 1982 and 1995, real world wheat prices declined by 28 percent, rice prices by 42 percent, and corn prices by 43 percent (computed from World Bank 1996a). The declining 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 therefore yields. This shift into more diversified cropping, while an appropriate farmer response to changing incentives, puts greater pressure on productivity growth in existing cereal areas. Probably more important in the long run, the declining world price has caused a slowdown in 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.

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 35 countries and regi of world food production and consumption), and 17 commodities, including all cereals, roots and tubers, meats, and dairy products. 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 hybridization 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).

World Food Prices

The baseline projections results of the IMPACT model indicate that food production in the world will grow fast enough that world prices of food will be falling, albeit at a slower rate than in recent years. Cereal prices on average are projected to drop by nearly 20 percent by 2020, and meat prices by about 10 percent. 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 double by 2020, reaching 183 million tons. What are the underlying trends in food demand and production that produce these projections of a continued (but much slower) decline in food prices?

Food and Feed Demand

The most important underlying trends on the demand side are rapidly increasing urbanization, changing tastes and preferences, and rising incomes, which are causing a shift to more diversified diets with higher per capita consumption of meat, milk and milk products, fruits, and vegetables, and lower per capita consumption of cereals. Thus, in China and much of Southeast Asia, per capita consumption of rice is already falling; and rates of growth in per capita 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.

These trends are apparent in the per capita demand growth in food and feed shown in Table 2. In Asia, per capita demand for wheat will grow annually at rates ranging from 0.7 percent in India to just over 1.0 percent in Southeast Asia. Growth in per capita consumption of rice in the different regions in Asia will range from slightly negative to 0.6 percent. In China, per capita demand for rice will continue to decline, while per capita demand for wheat and maize, on the other hand, will rise at the rate of 0.95 percent and 1.2 percent per year, respectively. In India, per capita demand growth for rice will be sliwth in per capita demand for wheat in India will be slightly lower than in Southeast Asia. Per capita growth in cereal in West Asia and Northern Africa (WANA) and Latin America will also be slow. With income barely surpassing population growth in Sub-Saharan Africa, per capita consumption of cereals and roots and tubers will grow very slowly.

Growth rates in total food and feed demand also indicate a slowdown in demand, due to both changes in the diet structure and the continued gradual slowdown in population growth (Table 3). The most rapid growth will be in regions with fastest population growth, even though per capita demand growth in these regions is slow. These include Sub-Saharan Africa, WANA, and Other South Asia, mainly Pakistan. The demand growth for maize in developing countries will primarily be for animal feeds: demand of maize for feed will more than double over the period shown, whereas demand of maize for food will grow slowly. This is due to the expansion of livestock industry, especially in the more rapidly growing developing economies, where consumption of meat will expand dramatically.

How will these demand growth rates translate into absolute demand requirements? Table 4 shows increases in total demand between 1990 and 2020. Total cereal demand will increase by about 1 billion metric tons during this period from 1.7 billion metric tons in 1990 to 2.7 billion metric tons in 2020. Eighty percent of this increase will come from the developing world, where both population and income effects are higher than in the developed economies. The almost 20 percent share of the developed countries will be mainly in maize and other coarse grains. China and India will jointly account for 35 percent of the total cereal demand increases. The rest of Asia will account for another 14 percent. Sub-Saharan Africa and WANA will each account for about 10 percent, and Latin America for 8 percent. Two thirds of the growth in wheat demand will be accounted for by China and WANA. Despite slow per capita growth, the absolute rice demand expansion in Asia will still be large, at 184 million metric tons.

Production, Area, and Yield Growth

World cereals production in the future is projected to grow at an average rate of 1.5 percent per annum. This annual rate of growth will be slower than the 1.7 percent annual growth in cereal production achieved during 1982 to 1996. Production trends can better be understood by looking at their component parts, yield and area. 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 63 million ha, from a total of 744 million ha in 1990. In Asia, crop area will increase by less than 6 percent 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 5). 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 1982-95 period (Table 6). For developing countries as a group, wheat yields are projected to grow at 1.8 percent per year (compared to 2.3 percent since 1982); rice yields at 1.5 percent (compared to 1.6 percent); and maize yields at 1.5 percent (compared to 2 percent). Rice yields in China are projected to grow at 1.0 percent per annum between 1990 and 2020, compared to the 1.6 percent annual growth rate since 1982. For wheat, the annual yield growth rate will be 1.5 percent, compared to the 2.7 percent 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, at around 2 percent per year (compared to yield growth rates in India of 2.6 percent for wheat and 2.7 percent for rice since 1982). 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 meeting rising populations and incomes? In the remaining sections of the paper, we examine these issues and discuss their implications for environmental and resource policy.

Cropland Potential and Land Loss to Urbanization

Cropland potential

In 1990, crop area harvested for cereal and root crops was 744 million ha (282.2 million ha in the developed world, and 461.9 million ha in the developing world); and, according to the IMPACT simulations shown above, this area will increase to 806.9 million ha by 2020, with virtually no increase in crop area in developed countries to 283.6 million ha, and a relatively large increase in developing countries to 523.4 million ha (Table 5) Cereal and root crop area represented about 72 percent of total crop area in 1990.

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 a study by 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 can be qualified as having zero potential for growing crops, 2,600 million ha have a low and medium capability for crop production, and 700 million ha have a high potential. Thus, the theoretical maximal potential would be at least 3,300 million ha suitable for crop production.

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 fulfill 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 percent is located in developing countries, mainly in Sub-Saharan Africa and Latin America. In Asia, on the other hand, nearly 80 percent of potentially arable land is already under cultivation, and land availability per capita are expected to be about 0.1 ha in China and India (Plucknett 1995).

Both, the theoretical maximal 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.

Land Loss to Urbanization

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 percent between 1995 and 2025. The majority of the population is projected to live in urban areas by 2025 (61 percent), up from 38 percent in 1975 and 45 percent in 1995. Whereas more than 70 percent of the population in both North America and Europe has been living in urban areas by 1995, urbanization accounted only for 34 and 35 percent in Africa and Asia, respectively. Almost all urban population growth, about 90 percent, 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 (U.S. AID 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 c the type of land converted into urban uses, as well as the final urban per capita land area. Historically, more potential cropland has been converted to agricultural activities and grazing than urbanization 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 percent 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 (see above), the loss of land to urbanization will not be a serious threat to the projected growth in crop area.

Physical Limits to Crop Productivity

Global food production can increase through expansion of cropping area and increases in cropping intensity (see above), or 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 for achieving the necessary production rates to meet global food demand. 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 selecop 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) have been calculated by Linneman et al. in 1979 (see Table 7). 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, the limits are much lower for northern and southern Africa and western Asia due mainly to limited water resources. 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 of between 10 and 18 tons per ha per year depending on the region. 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). Currently existing wide disparities in yields among countries in the same region and between continents also give rise to the expectation that considerable improvement could be achieved by farmers.

However, in order to maintain yield growth and to further increase the yield potential, agricultural research will be essential at several levels: productivity maintenance research in order to keep yield increases up; research to improve 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).

Plant Genetic Resources

Genetic Resource Availability

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 they allow 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 Evenson and Gollin 1994). Global *ex situ* storage of germplasm is substantial for the major food crops. The United States holds 557,000 accessions of crop germplasm, China 400,000, and Russia 325,000. The International Rice Research Institute (IRRI) has 86,000 holdings of rice germplasm; the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has 86,000 holdings for sorghum, millet, chickpea, peanut, and pigeon pea; and the International Maize and Wheat Improvement Center (CIMMYT) has 75,000 holdings for wheat and maize (Wright 1996). Approximately 75 to 90 percent of the estimated genetic variation in the major crops and about 50 percent for minor crops is found in gene banks (Wilkes 1992). Concerns, however, have been expressed over 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 at present appears sufficient to sustain future breeding efforts to support the moderate crop yield growth rates projected above.

Crop Genetic Diversity

Although the available germplasm is characterized by wide genetic variation, the number of varieties actually tapped and utilized 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 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.

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 techniques 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 from 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. In terms of impact on long-term crop yield growth, 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 $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 inherent in 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 centers 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, since most current agricultural biotechnology research undertaken in developed countries, which is aimed at plants suitable for temperate climates (Livernash 1996).

Fortunately, new institutional arrangements for biotechnology research linking developed and developing countries institutions have been put in place recently, and some developing countries, like China or India, have increased their annual budgets for their biotechnology 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 centers continue to grow, biotechnology will provide a significant boost to crop production in the next century.

Fertilizer

Historical Fertilizer Use

Can continued expansion of fertilizer use support the projected gains in crop yields without damaging the environment? Global fertilizer 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 fertilizer use is primarily the result of steep declines in fertilizer application in the reforming economies of Eastern Europe and the former Soviet Union (Bumb and Baanante 1996). However, a clear slowdown in growth in fertilizer consumption had already begun in the early 1980s. In the developed countries, fertilizer use grew at a rate of 3.7 percent per year from 1966 to 1982, but declined by 2.8 percent per annum after 1982.

Fertilizer use in developing countries grew at a rate of 12.4 percent per year from 1966 to 1994. However, there was a significant decline in the rate of growth in the early 1980s, with the growth rate in fertilizer use dropping from 10.5 percent during 1966-82 to 4.3 percent per year after 1982.. This decline was due mainly to price effects (rapidly declining real crop output prices), and, in some regions, intensification effects, as the achievement of high levels of fertilizer use reduced the profitability of further increases (Rosegrant and Pingali 1994). Despite this slowdown, by 1995, the developing countries' share in global fertilizer use had increased to 58 percent, compared with 10 percent in 1960 and 31 percent in 1980 (Bumb and Baanante 1996).

With long-term high growth rates in fertilizer use and declining growth rates in yield, fertilizer levels in relatively favorable areas of Asia are now quite high, and increasing amounts of fertilizer are being used to maintain current yield levels. In parts of Asia, including West Java in Indonesia, the Indian Punjab, and parts of China, fertilizers are being used at or above economically optimum levels at border prices. In East Asia, average fertilizer use is nearly 220 kg/ha. In much of this region, further increases in fertilizer application will be small, but there is considerable room for improvement in fertilizer use efficiency and uptake rates. Even in regions with high fertilizer application rates, crop productivity can be improved without expansion of fertilizer application by increased nutrient uptake efficiency and improved 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 fertilizer use. In South Asia, for example, fertilizer use is only about 80 kg/ha; in Latin America, 65 kg/ha; and in Sub-Saharan Africa, only about 20 kg/ha (Bumb and Baanante 1996).

Future Growth in Fertilizer Demand and Supply

Bumb and Baanante (1996) estimated effective demand growth for fertilizer, based on a behavioral model that takes into account the effect of economic and noneconomic variables, such as foreign exchange availability, exchange rate, crop and fertilizer prices, the development of irrigation and other infrastructure, and the impact of policy reforms on fertilizer demand. During the 1990-2020 period, global fertilizer demand is projected to increase 1.2 percent per year. In absolute amounts, fertilizer 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, 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. Fertilizer use in developing countries is projected to grow at 2.2 percent per year. While these fertilizer demand growth rates are relatively low, they are certainly adequate to support the projected yield growth rates shown above.

Can the production of fertilizer keep up with the projected effective demand for fertilizer? 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 fertilizer 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, fertilizer production should be increased at an annual rate of 1.4 percent during the 2000-2020 period to satisfy the projected effective fertilizer demand. Given the 5.7 percent annual growth in fertilizer 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 to meet future global fertilizer demand.

The one constraint that could slow the expansion of fertilizer capacity is continued low fertilizer prices. The real price of the urea in 1993 was only one-third of its 1980 price, before beginning to recover, and in 1995 was still only 60 percent 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 percent of their 1980 values. World Bank (1996b) projections indicate that fertilizer prices will be stable or slightly lower through 2005. If these price levels constrain future investment in fertilizer production capacity, fertilizer prices could increase in later years, which would induce a combination of a reduction in growth in fertilizer use combined with improved efficiency of fertilizer 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 fertilizer use, a 50 percent increase in real fertilizer prices (much higher than likely increases) would reduce crop yields in 2020 by only about 2 percent in absolute terms.

Fertilizer and the Environment

Are the projected rates of growth in fertilizer use a threat to the environment? The two major environmental effects of high levels of fertilizer 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 fertilizer and other sources exceeds nitrogen uptake by plants. Eutrophication occurs when fertilizer 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 of high fertilizer use are of considerable concern in Western Europe and parts of North America, and policies are being put in place to selectively reduce fertilizer use (Leuck et al. 1995). However, with the possible exception of intensively cultivated areas of East Asia and pockets of high fertilizer use elsewhere, fertilizer use in developing countries is so low that nitrate leaching and eutrophication do not pose a significant problem.

In many developing regions, and notably in Sub-Saharan Africa, it is not overuse of fertilizer, but insufficient use that causes harm to the environment. Inadequate replenishment of removed nutrients and organic matter reduce soil fertility and increase erosion rates. Between 1945 and 1990, nutrient depletion in Africa caused light degradation of 20.4 million ha of land, moderate degradation of 18.8 million ha, and severe degradation of 6.6 million ha (Oldeman et al. 1990). Given the extremely low use of fertilizer in Sub-Saharan Africa, increased fertilizer use, along with other complementary measures, can help reverse the 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 plowed 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).

Indeed, rapid expansion of fertilizer use is one of the keys to crop productivity growth in Sub-Saharan Africa. Although policy prescriptions of different observers vary, key policy elements to boost fertilizer use and crop yields in Sub-Saharan Africa include (a) continued reform of the agricultural policy environment, including price, exchange rate, marketing and input supply policies, to provide incentives for private sector investment in farming, marketing, and processing; (b) improved security of land tenure to induce conservation investments and improve access to credit; (c) increased investment in research and extension, rural infrastructure, improved fertilizer supply and distribution systems, and human capital development, including education, health, and nutrition; and (d) agroclimatic-specific targeting of research and extension efforts including location-specific research on soil fertility constraints and agronomic practices; (Cleaver 1993; Delgado and Pinstrup-Andersen

1993; Reardon et al. 1993; Harrison 1990; von Braun and Paulino 1990).

At the other end of the spectrum, the achievement of relatively high levels of fertilizer use on rice in Asia has shifted the concern from simply increasing the levels of use to improving the efficiency of fertilizer application. This must be done by improving the management and balance of fertilizer applications in order to deal with soil fertility constraints. Here, continued reduction and eventual elimination of fertilizer subsidies will be necessary to send the right signals for efficiency improvement (Rosegrant and Pingali 1994).

Energy and Agriculture

Direct (farm machinery, animal and human labor) 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 fertilizer 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 percent in 1982), followed by chemical fertilizers with an increasing share (44 percent in 1982). In developing countries, however, fertilizers take the first place with 69 percent of energy share in 1982 (Bhatia and Malik 1995).

Despite increases in energy intensity in agriculture, agricultural uses of energy account for only a fraction of total energy consumption. In 1990, only about 2 percent of global energy consumption the most energy-intensive agricultural input. By 2020, energy use in the fertilizer sector is expected to decrease to about 1.6 percent. This is partly due to increasing energy efficiency in fertilizer plants, which has improved considerably during the last two decades, especially since the energy crisis of the 1970s. The globalization and privatization of the fertilizer markets, as well as the removal of energy subsidies and inefficient organizational 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 percent of total farm production expenses in the United States. Together with expenditures for pesticides and fertilizers, the cost share augmented to between 11.2 and 17.2 percent 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 lead to only a small decline 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 percent drop in direct and indirect energy intensity in the production of one ton of wheat in one French region 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, for example.

As far as environmental constraints are concerned, agricultural production contributes to carbon dioxide emissions in the atmosphere, land degradation and pollution if fertilizers are applied above or below efficiency levels; and air and water pollution of consumption and production of energy based on fossil fuels will lead to further environmental degradation and depletion of fossil fuels. However, the conversion of energy used in agriculture into food production offers the most cost-effective form of energy resources use (Bumb and Baanate 1996).

Energy use has clearly been an essential factor for bringing about the Green Revolution in the 1960s, and will remain essential for achieving food security in the common 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.

Land Degradation

Prevalence of Land Degradation

There are serious problems from degradation of agricultural lands 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 basic environmental structure and function and, 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 which need to be addressed, these problems are in many cases localized, and will have little impact on global food security. Available estimates of the scope and severity of land degradation on a global basis, and the impact of this degradation on food production indicates 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 salinization, 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 4,048 million ha was forest and woodland, 3,212 million ha was permanent pasture, and 1,475 million ha was agricultural land. An estimated 1,964 million ha of land within these latter three categories has suffered from some degree of degradation. Water erosion accounts for 56 percent of land degradation, wind erosion for 28 percent, chemical degradation for 12 percent and physical degradation for 4 percent. However, for agricultural land, chemical degradation is much more important, accounting for 40 percent of the estimated 562 million ha of degraded agricultural land (Oldeman et al. 1990). Of the total degraded area, 84 percent is classified as having a "light" or "moderate" degree of degradation, while "strongly" or "extremely" degraded land accounts for 15 percent of the degraded area.

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 inputs 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 percent 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 percent to 40 percent across countries, with a mean of 8.2 percent for the continent and 6.2 percent for Sub-Saharan Africa (Scherr and Yadav 1996). National estimates of the crop productivity effects of land degradation are summarized by Scherr and Yadav (1996) for more than a dozen developing countries. Seven African countries with fairly comparable data show rates of 0.04 percent to 11 percent 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), utilizing the Oldeman et al. (1990) data base, 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 17 percent. This is equivalent to an annual rate of decline of 0.35 percent over the period. While this is not an insignificant loss, the impact of degradation was dwarfed by crop yield growth of 2.1 percent per year during 1966-95.

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 stabilize or reverse degradation. Overall 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.

Irrigation and Water Resources

Prevalence of Water Scarcity and Pollution

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 percent; in Sri Lanka, they have tripled; and in Thailand they have increased by 40 percent (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 costs of new development put 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 meter 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 meters 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 reuse 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 to 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 percent 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 utilization of water before it reaches salt sinks; and by reducing salinization and other water pollution that diminishes crop yield per unit of water. It is unclear how large each of these potential water savings are. Water use efficiency in irrigation in much of the developing world is typically in the range of 25 to 40 percent, while in urban supply systems, "unaccounted for water," much of which is direct water losses to the oceans, is often 50 percent 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 is not as dramatic, nor as easy to achieve as implied by these efficiency figures, because much of the water "lost" from irrigation systems is reused 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 reuse 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 percent, but the overall efficiency for the entire Nile river basin is estimated at 80 percent (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.

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 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 develop[illegible] of new water, both through impoundment of surface water and sustainable [illegible]ion of groundwater resources, and through expansion in the development of [illegible]ional 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.

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 generally 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 radiatively active 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 fertilization' effect that increases crop yields. Under experimental conditions, for rice, wheat, and over 90 percent of the world's plant species, the estimated effect from a doubling of CO_2 is a 30-percent yield increase. For maize, millet, sorghum, and sugar cane, the effect is a much lower 7-percent 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 liberalization, and medium population growth rates, assuming modest farm-level adaptations to climate change, and without the CO_2 fertilization effect, the net impact of climate change would be an estimated reduction in global cereal production of up to 5 percent 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 benefitting 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 fertilization effect, negative global cereal yield impacts are nearly eliminated (with estimate yield changes in the range of +1.0 percent and -2.5 percent) 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. Utilizing a modeling 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; that land use changes that accompany climate-induced shifts in cropland and permanent pasture are likely to raise additional social and environmental issues; 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 generally more positive: world cereal production increases by between +0.9 and 1.2 percent, even without CO_2 fertilization effects (Darwin et al. 1995).

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

Conclusions

This paper assesses the projections of future global food supply, based on the IMPACT model developed by IFPRI, in the context of possible environmental constraints to productivity growth. IMPACT projections indicate that food production will likely keep pace with growing populations and incomes, and real food prices will be stable or slowly declining over the next twenty years. However, environmental and resource constraints have not been explicitly included in these projections. In this paper we examined whether the crop area, yield and production projections are attainable given possible resource and environmental changes.

Among the concerns being raised for sustaining future increases in agricultural production is whether there will be enough cropland to feed the increasing population. However, existing cropland potential is far higher than required by the actual IMPACT projections of increases in cropland through the year 2020. Data on losses of cropland to urban uses are limited, but the estimated rates of loss could be accommodated through increases in cropping intensity and expansion of existing crop area. Thus, the primary constraint to further crop area expansion are not physical limitations, but the projected continued decline of real food prices, which makes further expansion of cropland unprofitable.

Increases in yield growth rates, considered to be the main engine of agricultural production growth, face eventual physical limits. However, projected crop yields for major food crops in 2020 are still far from these maximum theoretical yields. Nevertheless, in order to attain the projected yield levels, continued investment in agricultural research, especially directed towards developing country needs, will be essential. Apart from the overall requirement to sustain and increase research in crop yields, policy interventions will have to be directed towards regional needs. In some parts of the world, for example, most of Sub-Saharan Africa and Eastern India, crop yield growth will still be mainly through adoption of improved varieties and increased use of inputs. In other parts of the world, such as much of East Asia, where relatively high yields have been attained, future growth in crop productivity will increasingly come from improved management and efficiency of use of the scarce resources utilized in production.

Plant genetic resources are fundamental for providing raw material for plant breeding and thus for ensuring future growth in crop yields. Both the crop genetic variation embodied in germplasm stored *ex situ* in gene banks and genetic diversity embodied in modern cultivars appear sufficient to sustain future breeding efforts to support the crop yield growth rates projected here. The principal threat to adequacy of the genetic base would be a failure to sustain funding for proper documentation, evaluation, and maintenance of the existing system of germplasm banks.

Biotechnology will be increasingly important in generating projected yield gains as we approach 2020. For the next decade or two, additional yield increases in farmers' fields will continue to be produced by conventional plant breeding. As exhaustion of gains from conventional breeding begins early in the next century, further yield growth will be generated through a combination of conventional breeding with wide-crossing, transgenic crosses, and other tools resulting from biotechnology research. In order to fulfill the promise of biotechnology, sufficient funds must be allocated to biotechnology development for crops grown in developing countries, as well as to collaborative arrangements between the developed and developing world.

Fertilizer use has been an important factor in sustaining agricultural production growth and is projected to continue to play this role. Fertilizer production is expected to keep up with growing fertilizer demand without heavy pressure on prices or the environment. In some regions in the developed world and parts of Asia, however, excessive fertilizer application produces adverse environmental effects such as nitrate leaching and euthropication. In these regions, the focus of fertilizer policy should shift from solely increasing the level of use of fertilizer to also advancing the efficiency of the nutrient balance and the timing and placement of fertilizers to improve nutrient uptake. In Sub-Saharan Africa, by contrast, it is insufficient fertilizer application which may constrain food production and damage the environment. Here, reforms of the agricultural policy environment as well as location-specific research will be necessary to boost fertilizer use and thus crop yields.

Energy cannot be considered a resource constraint to future growth in agricultural production: agriculture uses only a very small portion of total energy use; energy use in agriculture is a small portion of agricultural production costs; there are signs, at least in the developed world, that as agricultural intensification continues, it may actually reduce the energy value per unit value of agricultural output; and real energy prices are projected to further decrease over the next decades.

Estimates of the impact of land degradation on crop yields are rare, but on a global basis, the yield impact of degradation appears to be very small relative to crop yield growth from technological change and increased quantity and efficiency of input use. Land degradation at current rates is not a serious impediment to global food supply, although degradation can be devastating in particular regions. Policy interventions should therefore be particularly directed at these local zones of risk. More broadly, land degradation should be attacked by correcting policy and institutional failures -- especially the failure to establish secure rights to land, which leads to overuse or overextraction as well as lack of investment in efficiency and conservation of the resource; market and pricing failures, including inappropriate subsidies that failed to take into account the external costs of different activities and decisions; and government failures, in terms of poorly managed bureaucracies, excessively extractive policies, and inability to regulate environmental damage.

Water scarcity and pollution may be the most serious threats to attainment of projected yield growth. Although water scarcity and pollution are region-, locale-, and season-specific, overall development of new water sources has become increasingly expensive and water used for irrigation, the most important use of water in developing countries, will likely have to be diverted to meet urban and industrial needs. To meet this challenge, it is necessary to generate both physical savings of water and economic savings by increasing crop output per unit of evaporative loss of water; to increase the utilization of water before it reaches salt sinks; and to reduce water pollution. However, it remains unclear how large each of these potential water savings are. 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, decentralization and privatization of water management functions, and utilization of incentives, including markets in tradable property rights, pricing reform and reduction in subsidies, and effluent or pollution charges.

Climate change probably constitutes the least tangible constraint for future agricultural production. Projected global warming will have no serious negative effects, and may even have slightly positive impacts on crop yields through the projections period considered here. However, for the very long-term, there might be pronounced negative impacts for several developing regions, in particular in the semi-arid tropics and sub-tropics, and equatorial regions. The implications of climate change for world agriculture, and even more so for individual regions, however, are highly uncertain. Policy interventions must be seen in this light, and could include increased research into heat resistant and low-water using crops, improvements in international trade of agricultural commodities, and a generally greater inclusion of populations in developing countries into food markets. In the broadest sense, these are policies already mentioned above to improve the flexibility of resource allocation in agriculture: removal of subsidies and taxes that distort incentives, establishment of secure property rights; and investments in research, education and training, and improvement of public infrastructure.

References

Alexandratos, Nikos, (ed.). 1995. *World agriculture: Towards 2010. An FAO study*. Chichester, U.K.: John Wiley and Sons, and FAO, Rome.

Alt, K.; C. Osborn, and D. Colaccio. 1989. *Soil erosion: What effect in agricultural productivity?* Agriculture Information Bulletin No. 556, Economic Research Service. Washington, D.C.: United States Department of Agriculture.

Bhatia, Ramesh, and R. P. S. Malik. 1995. Energy demand and supply for sustainable agriculture: A vision for 2020. IFRPI mimeo. Washington, D.C.: IFPRI

Bonny, Sylvie. 1993. Is agriculture using more and more energy? A French case study. *Agricultural Systems* 43: 51-66.

Braun, J. von, and L. Paulino. 1990. Food in Sub-Saharan Africa: Trends and policy challenges for the 1990s. *Food Policy* 15 (6): 505-517.

Brown, Lester R., and Hal Kane. 1994. *Full house: Reassessing the earth's population carrying capacity*. New York: W. W. Norton.

Brown, Lester R. 1995. *Who will feed China?: Wake-up call for a small planet.* New York: W. W. Norton & Company.

Bumb, Balu L. 1995. *Global fertilizer perspective, 1980-2000: The challenges in structural transformation.* T-42. Muscle Shoals, Ala., U.S.A.: International Fertilizer Development Center.

Bumb, Balu L., and Carlos A. Baanante. 1996. *The role of fertilizer in sustaining food security and protecting the environment to 2020.* 2020 Vision for Food, Agriculture, and the Environment Discussion Paper No. 17, Washington, D.C.: IFPRI.

Buringh, P., and R. Dudal. 1987. Agricultural land use in space and time. In *Land transformation in agriculture*, eds. M. G. Wolman and F. G. A. Fournier. New York: John Wiley.

Byerlee, Derek. 1994. Technology transfer systems for improved crop management: Lessons for the future. In *Agricultural technology: Policy issues for the international community*, ed. Jock R. Anderson, Wallingford, U.K.: CAB International.

Cassman, K. G. (ed.). 1994. *Breaking the yield barrier: Proceedings of a workshop on rice yield potential in favorable environments.* IRRI, 29 November - 4 December 1993, Manila, Philippines: IRRI.

Cassman, K. G., and R. R. Harwood. 1995. The nature of agricultural systems: Food security and environmental balance. *Food Policy*, Vol. 20, No. 5, pp. 429-454.

Cleaver, K. 1993. Green revolution directions: Summary of workshop meetings. Summary discussion for the 1993 American Agricultural Economics Association preconference workshop Post-Green Revolution Agricultural Development Strategies in the Third World: What Next?, Orlando, Fla.

Cohen, Joel I. 1994. *Biotechnology priorities, planning, and policies: A framework for decision making*. Research Report No. 6, The Hague, The Netherlands: ISNAR (International Service for National Agricultural Research).

Crosson, Pierre. 1986. Sustainable food production: Interactions among natural resources, technology and institutions. *Food Policy* 11: 143-156.

______ 1995. *Soil erosion and its on-farm productivity consequences: What do we know?* Discussion Paper 95-29, Washington, D.C.: Resources for the Future.

Crosson, Pierre, and Jock R. Anderson. 1992. *Resources and global food prospects: Supply and demand for cereals to 2030*. Technical Paper 184, Washington, D. C: World Bank.

Darwin, Roy; Marinos Tsigas; Jan Lewandrowski, and Anton Raneses. 1995. *World agriculture and climate change. Economic Adaptations*. Agricultural Economic Report Number 703, Washington, D.C.: United States Department of Agriculture.

Delgado, C. L., and P. Pinstrup-Andersen. 1993. Agricultural productivity in the Third World: Patterns and strategic issues. Keynote address to the 1993 American Agricultural Economics Association preconference workshop Post-Green Revolution Agricultural Development Strategies in the Third World: What Next?, Orlando, Fla.

Downing, Thomas E. 1993. The effects of climate change on agriculture and food security. *Renewable Energy*, Vol. 3, No. 4/5, pp. 491-97.

Dregne, H. E., and N. T. Chou. 1992. Global desertification dimensions and costs. In *Degradation and restoration of arid lands*, ed. H. E. Dregne. Lubbock Tex., U.S.A.: Texas University.

Evenson, Robert E., and Mark W. Rosegrant. 1993. Determinants of productivity growth in Asian agriculture. Paper presented at the 1993 American Agricultural Economics Association preconference workshop, Post-Green Revolution Agricultural Development Strategies in the Third World: What Next? Orlando, Fla., U.S.A.

Evenson, Robert E., and Douglas Gollin. 1994. *Genetic resources, international organizations, and rice varietal improvement.* Center Discussion Paper No. 713, Yale University, New Haven, CT: Economic Growth Center.

FAO. 1996. FAOStat-PC. Land Use Domain, Internet Dissemination Tool, FAO Rome.

Harrison, P. 1990. Sustainable growth in African agriculture. In *The long-term perspective study of Sub-Saharan Africa.* Vol. 2, *Economic and sectoral policy issues.* Washington, D.C.: World Bank.

Kasperson, Jeanne X.; Roger E. Kasperson, and B. L. Turner II. 1996. Regions at risk: Exploring environmental criticality. *Environment*, Vol. 38, No. 10, pp. 4-15 and 26-29.

Kathen, A. de. 1996. *Gentechnik in Entwicklungsländern: Ein Überblick: Landwirtschaft.* Berlin, Germany: Umweltbundesamt.

Keller, J. 1992. Implications of improving agricultural water use efficiency on Egypt's water and salinity balances. In *Roundtable on Egyptian Water Policy*, ed. M. Abu-Zeid and D. Seckler. Proceedings of a seminar on Egyptian water policy, sponsored by the Water Research Center, the Ford Foundation, and Winrock International, at the Hotel Helnan International Palestine in Alexandria, Egypt, April 11–13. Publisher: Cairo, Egypt: Water Research Center, Ministry of Public Works and Water Resources.

Kendall, H. W., and D. Pimentel. 1994. Constraints on the expansion of the global food supply. *Ambio*, Vol. 23, No. 3. pp. 198-205.

Lal, R. 1995. Erosion-crop productivity relationships for soils in Africa. *American Journal of Soil Science Society* 59:661-667.

Leisinger, Klaus M. 1995. *Sociopolitical effects of new biotechnologies in developing countries.* 2020 Vision for Food, Agriculture, and the Environment Discussion Paper No. 2, Washington, D.C.: IFPRI.

Leuck, D.; S. Haley; P. Liapis, and B. McDonald. 1995. *The EU nitrate directive and CAP reform: Effects on agricultural production, trade, and residual soil nitrogen.* Report 225. Washington, D.C.: U.S. Department of Agriculture, Economic Research Service.

Linneman, H.; J. De Hoogh; M. A. Keyser, and H. D. J. Van Heemst. 1979. Potential world food production. In *MOIRA. Model of International Relations in Agriculture. Report of the Project Group on Food for a Doubling World Population*, 34-74. Amsterdam: North Holland Publishing Co.

Livernash, Robert. 1996. Agricultural biotechnology in developing countries. IFPRI mimeo. Washington, D.C.: IFPRI.

McDonald, Bradley J.; Stephen W. Martinez; Miranda Otradovsky, and James V. Stout. 1991. A global analysis of energy prices and agriculture. USDA (United States Department of Agriculture) Economic Research Service, Agricultural and Trade Analysis Division, USDA: Washington, D.C.

McNeely, J. A.; K. R. Miller; W. V. Reid; R. A. Mittermeir, and T. B. Werner. 1990. *Conserving the world's biological diversity.* Gland, Switzerland and Washington, D.C.: International Union for the Conservation of Nature and Natural Resources, World Resources Institute, Conservation International, World Wildlife Fund, World Bank.

Mitchell, Donald O., and Merlinda D. Ingco. 1993. *The World Food Outlook.* International Economics Department, Washington, D.C.: The World Bank.

Morris, Michael, and Derek Byerlee. 1996. Maintaining productivity gains in post-green revolution Asian agriculture. Mimeo.

Oldeman, L. R.; R. T. A. Hakkeling, and W. G. Sombroek. 1990. *World map of the status of human-induced soil degradation: An explanatory note.* Wageningen: International Soil Reference and Information Center; Nairobi: United Nations Environment Programme.

Paulino, L., and J. W. Mellor. 1984. The food situation in developing countries: Two decades in review. *Food Policy* 9 (4): 291-303.

Penning de Vries, F. W. T.; H. Van Keulen; R. Rabbinge, and J. C. Luyten. 1995. *Biophysical limits to global food production.* 2020 Vision Brief No. 18, Washington, D.C.: IFPRI.

Persley, Gabrielle J. 1994. Biotechnology's promise. In *Agricultural technology: Policy issues for the international community*, ed. Jock R. Anderson, Wallingford, U.K.: CAB International.

Pierce, F.; R. Dowdy; W. Larson, and W. Graham. 1984. Soil productivity in the corn belt: An assessment of erosion's long-term effect. *Journal of Soil and Water Conservation* 39(2): 131-136.

Pingali, Prabhu L. 1994. Technological prospects for reversing the declining trend in Asia's rice productivity. In *Agricultural technology: Policy issues for the international community*, ed. Jock R. Anderson, Wallingford, U.K.: CAB International.

Plucknett, Donald L. 1995. Prospects of meeting future food needs through new technology. In *Population and food in the early twenty-first century: Meeting future food demand of an increasing population*, ed. Nurul Islam, Washington, D.C.: IFPRI.

Postel, S. 1993. Water and agriculture. In *Water in crisis: A guide to the world's fresh water resources*, ed. P. H. Gleick. New York: Oxford University Press.

Reardon, T.; E. Crawford; R. Bernstein; C. Eicher; T. Jayne; U. Oehmke, and K. Savadago. 1993. Challenges for creating and sustaining a Green Revolution in Africa. Paper presented at the 1993 American Agricultural Economics Association preconference workshop, Post-Green Revolution Agricultural Development Strategies in the Third World: What Next? Orlando, Fla., U.S.A.

Reilly, John. 1995. Climate change and agriculture - Research findings and policy considerations. In *Population and food in the early twenty-first century: Meeting future food demand of an increasing population*, ed. Nurul Islam, Washington, D.C.: IFPRI.

Rosegrant, Mark W. 1995. Water resources in the 21st century: Increasing scarcity, declining quality, and implications for action. Paper presented at the Conference on the Sustainable Future of the Global System, organized by the United Nations University and the National Institute for Environmental Studies, Japan, October 15-18.

Rosegrant, Mark W., and Mark Svendsen. 1993. Asian food production in the 1990s: Irrigation investment and management policy. *Food Policy* 18 (2): 13–32.

Rosegrant, Mark W., and S. Shetty. 1994. Production and income benefits from improved irrigation efficiency: What is the potential? *Irrigation and Drainage Systems* 8 (4): 251–270.

Rosegrant, Mark W., and Prabhu L. Pingali. 1994. Policy and technology for rice productivity growth in Asia. *Journal of International Development*, 6: 665-688.

Rosegrant, Mark W., and Ruth Meinzen-Dick. 1996. Water resources in the Asia-Pacific region: Managing Scarcity. *Asia-Pacific Economic Literature*, pp. 32-53.

Rosegrant, Mark W.; Mercedita Agcaoili-Sombilla, and Nicostrato D. Perez. 1995. *Global food projections to 2020: Implications for investment*. 2020 Vision for Food, Agriculture, and the Environment Discussion Paper No. 5, Washington, D.C.: IFPRI.

Rosenzweig, Cynthia; Martin L. Parry; Günther Fischer, and Klaus Frohberg. 1993. *Climate change and world food supply*. Research Report No. 3, University of Oxford, Great Britain: Environmental Change Unit.

Scherr, Sara, and Satya Yadav. 1996. *Land degradation in the developing world: Implications for food, agriculture, and the environment to 2020.* 2020 Vision for Food, Agriculture, and the Environment Discussion Paper No. 14, Washington, D.C.: IFPRI.

Schimmelpfennig, David; Jan Lewandrowski; John Reilly; Marinos Tsigas, and Ian Parry. 1996. *Agricultural adaptation to climate change. Issues of longrun sustainability.* Agricultural Economic Report Number 740, Washington, D.C.: United States Department of Agriculture.

Seckler, David. 1996. *The new era of water resource management: From "dry" to "wet" water savings.* Research Report No. 1, Colombo, Sri Lanka: IIMI.

Smale, M. 1996. *Understanding global trends in use of wheat diversity and international flows of wheat genetic resources.* Economics Working Paper 96-02. Mexico, D.F.: CIMMYT.

Smale, M., and T. McBride. 1996. Understanding global trends in the use of wheat diversity and international flows of wheat genetic resources. Part 1 of *CIMMYT 1995/96 world wheat facts and trends: Understanding global trends in the use of wheat diversity and international flows of wheat genetic resources.* Mexico, D.F.: CIMMYT.

U.S. Aid. 1988. *Urbanization in the developing countries.* Interim report to Congress, Washington, D.C.: U.S. Aid.

Wheeler, David L. 1995. The search for more-productive rice. *Chronicle of Higher Education*, December, p. A12

Wilkes, Garisson. 1992. Strategies for sustaining crop germplasm preservation, enhancement, and use. *Issues in Agriculture* 5, 62. Washington, D.C.: Consultative Group on International Agricultural Research CGIAR Secretariat.

Wolfe, David. 1996. Potential impact of climate change on agriculture and food supply. In *Sustainable development and global climate change: Conflicts and connections*, eds. James White, William R. Wagner, and Wendy H. Petry. Proceedings of a conference sponsored by the Center for Environmental Information, Inc., 4-5 Dec 1995, in Washington, D.C., and published with the assistance of the US Global Change Research Program (USGCRP).

World Bank. 1993. *Water resources management.* A World Bank Policy Study. Washington, D.C.: World Bank.

_____ 1996a. International Economics Department, Washington, D.C.: World Bank.

_____ 1996b. Commodity markets and the developing countries: A World Bank quarterly. International Trade Division, November, Washington, D.C.: World Bank.

World Bank/FAO, UNIDO/Industry Fertilizer Working Group. 1994. *World and regional supply and demand balances for nitrogen, phosphate, and potash, 1992/93-1998/99*. Washington, D.C.: World Bank.

WRI (World Resources Institute). 1994. World resources 1994-95. New York: Oxford University Press.

_____ 1996. World resources 1996-97. New York: Oxford University Press.

Wright, Brian D. 1996. *Crop genetic resource policy: Towards a research agenda.* EPTD (Environment and Production Technology Division) Discussion Paper No. 19, Washington, D.C.: IFPRI.

Yudelman, Montague. 1996. The impact of biotechnology on crop production in developing countries. IFPRI mimeo, Washington, D.C.: IFPRI.

Table 1: Crop area, production and yield growth rates in percent, 1966-1995.[a]

	1966-95			1966-82			1982-95		
	Area	Prod.	Yield	Area	Prod.	Yield	Area	Prod.	Yield
Wheat									
Developed	-0.55	1.10	1.66	-0.07	2.13	2.21	-1.11	-0.06	1.05
Developing	0.97	4.10	3.10	1.48	5.35	3.81	0.40	2.69	2.29
World	0.07	2.19	2.12	0.52	3.15	2.63	-0.45	1.10	1.55
Maize									
Developed	0.34	2.19	1.84	0.65	3.09	2.36	-0.02	1.17	1.25
Developing	1.02	3.43	2.39	0.73	3.51	2.77	1.35	3.33	1.95
World	0.77	2.69	1.91	0.70	3.24	2.52	0.85	2.06	1.21
Paddy Rice									
Developed	-0.14	0.46	0.60	-0.05	0.27	0.32	-0.24	0.69	0.93
Developing	0.58	2.64	2.05	0.83	3.27	2.42	0.28	1.92	1.63
World	0.55	2.49	1.93	0.80	3.05	2.23	0.27	1.85	1.58

[a] Based on three-year moving averages.
Source: IMPACT Simulations.

Table 2: Per capita demand growth rates for various crops, by region, in percent, 1990-2020.

	Rice	Wheat	Maize	Other Grains	Roots/ Tubers
China	-0.06	0.95	1.20	0.01	-0.23
India	0.62	0.72	0.43	0.24	0.39
SE Asia	0.33	1.05	1.02	0.86	0.06
O S Asia	0.27	0.74	0.25	0.21	0.26
SS Africa	0.33	0.18	0.14	0.19	0.08
L America	0.59	0.35	0.41	0.59	0.15
WANA	0.12	0.11	-0.32	0.12	-0.28
Developed	0.17	0.16	0.38	0.45 454545	0.07
Developing	-0.07	0.51	0.50	0.36	0.00
World, total	0.07	0.13	0.08	-0.10	0.17

Source: IMPACT Simulations.

Table 3: Total demand growth rates for various crops, by region, in percent, 1990-2020.

	Rice	Wheat	Maize	Other Grains	Roots/ Tubers
China	0.84	1.86	2.11	0.91	0.56
India	2.23	2.33	2.03	1.84	1.99
SE Asia	1.82	2.55	2.52	2.36	1.55
O S Asia	2.58	3.07	2.57	2.53	2.58
SS Africa	3.22	3.07	3.02	3.08	2.96
L America	1.97	1.73	1.79	1.97	1.52
WANA	2.31	2.30	1.86	2.31	1.91
Developed	0.51	0.58	0.80	0.87 454545	0.64
Developin g	1.67	2.19	2.18	2.03	1.77
World, total	1.62	1.55	1.49	1.31	1.38

Source: IMPACT Simulations.

Table 4: Increase in total demand for various crops, by region, in million metric tons, between 1990 and 2020.

	Rice	Wheat	Maize	Other Grains	Roots/ Tubers
China	37.2	78.2	72.9	5.4	31.7
India	70.0	47.7	7.4	20.0	17.4
SE Asia	48.5	5.3	18.5	0.8	15.1
O S Asia	28.2	31.3	2.8	1.0	4.2
SS Africa	11.2	10.1	30.7	42.4	141.1
L America	9.1	17.3	40.5	9.1	27.3
WANA	5.8	70.7	10.3	5.8	9.3
Developed	2.9	45.6	70.0	70.8 454545	46.9
Developing	214.1	264.4	196.4	100.1	248.9
World, total	217.0	310.0	266.5	170.9	295.8
% Increase	62.5	58.4	55.9	47.7	50.8

Source: IMPACT Simulations.

Table 5: Crop area harvested, cereal and root crops, by region, in million hectares, 1990 and 2020.

	1990	2020	Increase, 1990-2020
China	101.8	107.3	5.5
India	104.6	109.7	5.2
SE Asia	51.2	55.1	3.9
O S Asia	27.6	29.4	1.8
SS Africa	70.4	102.8	32.5
L America	52.4	57.4	4.9
WANA	49.8	57.0	7.3
Developed	282.2	283.6	1.4
Developing	461.9	523.4	61.5
World, total	744.0	806.9	62.9

Source: IMPACT Simulations.

Table 6: Yield growth rates for various crops, by region, in percent, 1990-2020.

	Rice	Wheat	Maize	Other Grains	Roots/ Tubers
China	0.97	1.49	1.63	1.15	0.64
India	2.07	1.98	1.78	1.83	1.27
SE Asia	1.67	0.20	1.54	0.75	0.69
O S Asia	2.09	1.82	1.38	1.10	1.19
SS Africa	1.62	1.96	1.71	1.62	1.81
L America	1.54	1.68	1.58	1.54	1.06
WANA	1.53	2.14	1.74	1.53	1.39
Developed	0.75	0.99	0.92	0.94 454545	0.74
Developing	1.46	1.77	1.52	1.47	1.04
World, total	1.42	1.35	1.08	1.02	0.90

Source: IMPACT Simulations.

Table 7: Theoretical maximum production of grain equivalents per hectare of the continents and the world.

Region	Tons per ha per year
South America	18.0
Africa	14.2
Asia	13.1
North and Central America America A	11.2
Europe	10.4
Australia	10.4
Total average (world)	13.3

Note: Differences in continents are due to variations in land quality, solar radiation, number of potential cropping days, among others.

Source: Linneman et al. 1979 in Plucknett 1995.