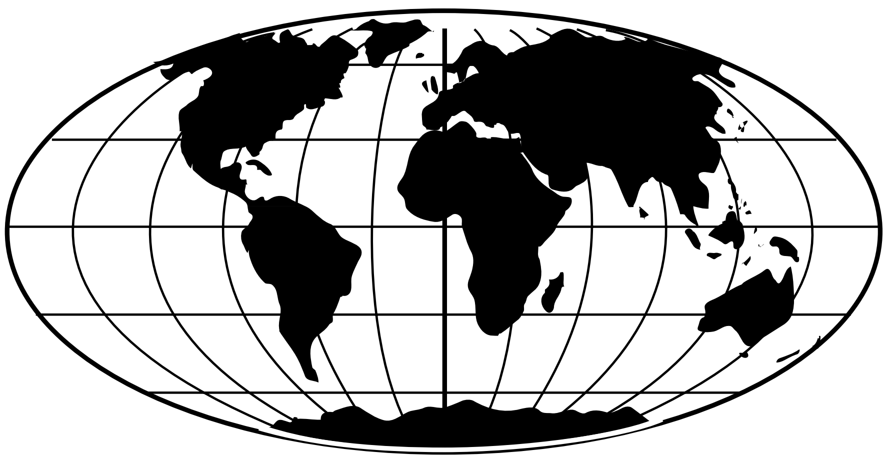
An Analysis of the Potential Demand for Phosphate Fertilizers: Sources of Change and Projections to 2025



March 1998

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International Fertilizer Development Center
P.O. Box 2040
Muscle Shoals, Alabama 35662, U.S.A.

Telephone: 205-381-6600
Telefax: 205-381-7408
E-Mail: general@IFDC.org
Web Site: http://www.ifdc.org

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by

Carlos A. Baanante

and

Deborah T. Hellums

International Fertilizer Development Center (IFDC

P.O. Box 2040

Muscle Shoals, Alabama 35662, U.S.A.

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The authors are, respectively, Director of the Research and Development Division and Soil Scientist in the same Division of the International Fertilizer Development Center, Muscle Shoals, Alabama, U.S.A.

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Carlos A. Baanante and Deborah T. Hellums

International Fertilizer Development Center (IFDC)

P.O. Box 2040, Muscle Shoals, Alabama, U.S.A.

Abstract

The demand for phosphate (P) fertilizers and other agri-inputs is derived from the demand for agricultural products. It is therefore determined by (a) factors that affect the structure and expansion of the demand for food and fiber, such as, growth in population and income and changes in preferences of consumers; (b) agricultural production technology used to manage natural resources and labor and capital as factors of production; (c) the endowment of natural resources, namely, land, water, and climate; (d) the policy environment; and (e) socio-cultural and environmental concerns affecting the behavior of farmers with respect to agricultural production. In this paper, the expected impact of all these factors on the potential demand for P fertilizers projected to the year 2025 is discussed. Growth in the demand for food associated with expected growth in population and income and increased preferences for poultry and livestock products, in conjunction with increased scarcity of land and water resources, are identified as the major sources of change in the demand for P fertilizers in the next 25-30 years. Increases in food production to satisfy future additional demand are expected to occur mainly as a result of agricultural intensification implemented to increase the productivity of the limiting resources of land and water. The increased and more efficient use of mineral fertilizers, including P fertilizers, in conjunction with improvements in the management of land and water resources, and the use of other inputs and improved biological technology are required to achieve sustainable expansion of land productivity and food production. The annual rate of growth of demand for P fertilizers in terms of P_2O_5 during 1990-2025 is expected to be a fraction (about one-fourth or one-third) of the rate of growth achieved during 1960-1990. Global consumption of P fertilizers is projected to increase from 37.5 million tons of P_2O_5 in 1990 to about 60 million tons in 2025. Growth in demand in absolute quantities will be substantial in Asia, Latin America, Africa, and North America, lower in Eastern Europe and Oceania, and negative in Western Europe and the former Soviet Union (Eurasia). Because of uncertainty about the implementation of a conducive policy environment, demand projections for countries in Africa, Eastern Europe, and Eurasia are more uncertain than those made for Western Europe, Oceania, and North America.

Disparity in the expansion of demand in various countries and regions with respect to the locations where the expansion of production of P fertilizers will take place will increase significantly the volume of fertilizers traded among countries. The widespread adoption of policies to liberalize trade and technical improvements in communication and information systems should improve significantly the efficiency of trade at the global level. Analyses of data,

trends and projections show that the increased need for agricultural intensification in Asia, Africa, and Latin America will be the major source of expansion in demand for P fertilizers in the first 2-3 decades of the 21st century. Environmental concerns will cause a decline in the demand for P fertilizers in Western Europe and may adversely affect the expansion of demand in North America.

A. Introduction

Phosphorus (P) plays essential roles in both the plant and animal life. It is the major component of the organic compounds, which serve as the primary sources of energy for most biochemical processes. Phosphorus is also an essential structural component of a variety of biochemicals, including nucleic acids that are the templates for genetic inheritance and protein synthesis. In terms of plant growth, sufficient P nutrition improves a number of plant processes including photosynthesis, nitrogen fixation, flowering, fruiting, seed formation, root development, and crop maturation. Despite its importance, low concentrations of P are present in the soil-plant-animal continuum, and in most agricultural systems it must be provided as an external input if efficient sustained crop production is to be obtained.

History has shown that if soil nutrients removed in agricultural products are not replenished, nutrient depletion results in reduced agricultural productivity and eventually land degradation. Prior to the availability and use of mineral fertilizers, various techniques including shifting agriculture, extensive use of animal manure, and the growth of legumes were utilized in attempts to replenish nutrients removed by crops. Most of these attempts were not successful, and despite what many believe today, this type of agriculture did not function well. Farming was inefficient and kept vast numbers of the population tied to the land to produce food. Also, despite the use of fallows and legumes in rotation, the systems were not sustainable due to soil nutrient mining and depletion resulting from low nutrient inputs and poor soil conservation practices. For example, in the United States, during the Dust Bowl years, approximately one-third more land was being cultivated than is currently under cultivation, however, yields were only a fraction of what they are today. The damage to the environment from these practices was substantial due to large areas of land required for such agriculture (Byrnes and Bumb, 1998).

Similar practices continue in much of the developing world where increased food demands combined with a lack of arable land, and/or the lack of external inputs, are forcing farmers to mine soil nutrients while simultaneously reducing the fallow period. The most pressing example is in sub-Saharan Africa where current mineral fertilizer use averages less than 10 kg per ha, a level that is far below what is needed to replace the nutrients removed in annual harvested crops. These actions are accelerating nutrient depletion of low fertility soils and prompting many farmers to cultivate so-called marginal lands that are extremely susceptible to degradation. In these soils, fertilizers—particularly phosphate fertilizers—will be important for halting this downward spiral of land degradation and the resulting increase in poverty.

Judicious application of fertilizer inputs provides for a readily available source of nutrients to support plant growth and increased sustained productivity. While each nutrient has a specific role in supporting plant growth, all the essential nutrients work together to maintain soil fertility, soil productivity and prevent land degradation. If the role of P is viewed in the broad context of maintaining land productivity and soil conservation, then it can be seen that P has both direct and indirect effects. The increased availability of P has a positive direct effect on the quantity and quality of agricultural outputs. Also, through indirect interactive effects it increases the response of agricultural production to other inputs such as nitrogen (N) and potassium (K) and has positive effects on the impact of biological N fixation, soil organic matter maintenance, water-holding capacity, soil erosion control and other soil physical and chemical properties. All of these positive effects result in increased agricultural output, sustained productivity and land conservation (Baanante, 1998).

Mineral fertilizers are the primary external sources of plant nutrients required to achieve substantial increases to agricultural production and land productivity. They are produced mainly to meet the demand for the major plant nutrients of nitrogen (N), phosphate (P_2O_5), and potassium (K_2O) in agricultural production. Thus, the demand for fertilizers is derived from the demand for agricultural products. Changes in the demand for fertilizers, including phosphate fertilizers in particular, are, therefore, determined by changes in factors that affect the demand for agricultural products—mainly food—and also by changes in agricultural production technology. Hence, the following more specific set of factors and circumstances influence the demand for fertilizers: (a) factors determining the structure and expansion of the demand for food, such as, population and income growth and changes in preferences of consumers; (b) changes in agricultural production technology affecting the management of natural resources, labor, capital and variable external inputs in agricultural production; (c) changes in the endowment of natural resources—stock of "natural capital of land and water"—affecting the sustainability of agriculture productivity; (d) changes in the policy environment; and (e) concerns and perceptions of policymakers, farmers and consumers affecting the conservation of the resource base and the environment and their behavior with respect to agricultural production and resource conservation. Finally, the demand for fertilizers is affected by exogenous climatic factors.

In the following sections, first, a conceptual framework of the derived demand for P fertilizer is presented, and the most important sources of change that are expected to affect the demand in the next 25-30 years at the regional and global levels are discussed. Then, country-level and regional data are used to estimate models to (a) project the demand for P fertilizers to the year 2025, and (b) evaluate the main sources of change affecting (and explaining) the expansion in demand for P fertilizers. Finally, implications of future growth in demand for food and fertilizers on economic development issues such as international trade, food security, and resource conservation are discussed.

B. The Demand for P Fertilizers

The demand for agricultural products and the nature of agricultural production are the key determinants of the demand for all agricultural inputs, including P fertilizers. Thus, general models of the functions of demand for and production of agricultural products are specified and used here as the basic framework to derive a general model of the demand function for P fertilizers.

A general model of the aggregate demand function for food and agricultural products can be specified as follows:

$$Y_d = F(P_y, P_o, I_c, T_a), \qquad (1)$$

where the quantity demanded of food and agricultural products Y_d is a function of the prices or a price index of agricultural products P_y, the human population P_o, the income per capita I_c, and the taste and preferences of consumers T_a. The main "shifters" of the demand function (P_o, I_c, and T_a) are the main sources of expansion and change in the demand for food and agricultural products.

A general model of the aggregate production function for food and agricultural products is specified as follows:

$$Y_p = \Phi(\overline{X}, \overline{D}, K, L, T_o), \qquad (2)$$

where the quantity of food and agricultural output produced Y_p, is a function of a vector of variable inputs $\overline{X}$, including P fertilizers (X_i), a vector of climate and soil factors $\overline{D}$, capital K, land L, and the level of production technology T_o. Then a general model of the derived static demand for P fertilizers X_i is:

$$X_i = g(P_{xi}, \overline{P}_{xj}, P_y, \overline{D}, K, L, T_o), \qquad i \neq j. \qquad (3)$$

In this model, the quantity of the variable input X_i (P fertilizers) depends upon the price of P fertilizer P_{xi}, the prices of all other variable inputs $(\overline{P}_{xj})$, a price index of agricultural products P_y, climate and soil factors $\overline{D}$, capital K, land L, and technology T_o as defined above. Thus, the main sources of change of the demand for P fertilizers associated with agricultural production are changes in (a) prices of variable inputs and agricultural outputs; (b) climate and soil factors; (c) availability and cost of capital; (d) availability and quality of arable land, and (e) the level of production technology embodied in the inputs used and in the management of all resources.

In equilibrium, the quantity of food and agricultural products produced Y_p should be equal to the quantity demanded Y_d. Therefore, over time, changes in factors that affect the demand for food also affect the demand for P fertilizers, and for all other variable inputs (other fertilizers, pesticides, seeds) and factors of production such as land and water.

From equations (1) and (2), the main possible sources of change and expansion in demand for P fertilizers, in addition to prices of inputs and outputs, can be identified. First, population growth and changes in per capita income and tastes and preferences of consumers affect the demand for P fertilizers as a result of their influence on the demand for food and agricultural products. Secondly, the availability of land and water, soil and climate factors, and the availability and prices of other variable inputs and capital are, in addition to the "level" of agricultural production technology, the other key sources of change and expansion in the demand for P fertilizers. In the following sections, the expected influence and contributions of these factors on the future demand for P fertilizers is assessed and discussed.

C. Sources of Change Affecting the Future Demand for P Fertilizers

1. Growth and Changes in Demand for Food

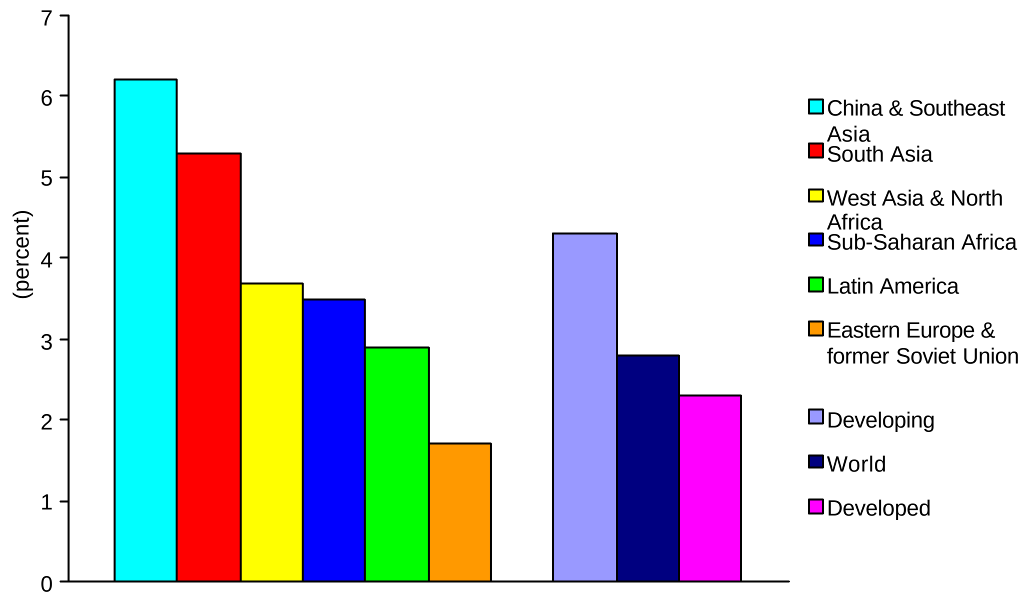
Growth in the demand for food is influenced by changes in a number of forces but mainly by population growth, income levels and economic growth, and changes in the preferences of consumers. Although the United Nations recently adjusted downward its estimates of population growth, it is expected that during the next 25-30 years about 80 million people will be added to the world's population each year, increasing it from about 5.7 billion in 1995 to about 7 billion by 2025. More than 95% of the population growth will take place in the developing countries and although the absolute population increase will be the highest in Asia, the relative increase will be greatest in sub-Saharan Africa.

Because much of the population growth in the developing countries is expected in the cities (urban population is expected to double in the developing world over the next 25 years; United Nations, 1995), patterns of food demand will change significantly as a result of urbanization. Preferences of consumers will shift from basic staples such as millet and sorghum to cereals such as rice and wheat and to fruits and vegetables, livestock products, and processed foods that require less preparation time.

Income per capita is a key determinant of the access to food by people. More than 1.3 billion people currently have incomes of a dollar a day or less per person and therefore have very limited access to (demand for) food. Another 2 billion are only marginally better off (World Bank, 1997). Rates of growth of income in recent years have varied considerably between countries and regions. Global income growth is projected to average 2.7 percent per year between 1993 and 2020. On the average, income growth rates in the developing countries as a group are expected to be almost twice as high as those in the developed countries (IFPRI, IMPACT Simulations in Pinstrup-Andersen *et al*., 1997). Eastern Europe and the former Soviet Union are expected to have the lowest growth rates in the next 25-30 years (Figure 1). In addition, significant disparities in income levels and growth rates among and within countries are expected to persist during the coming decades.

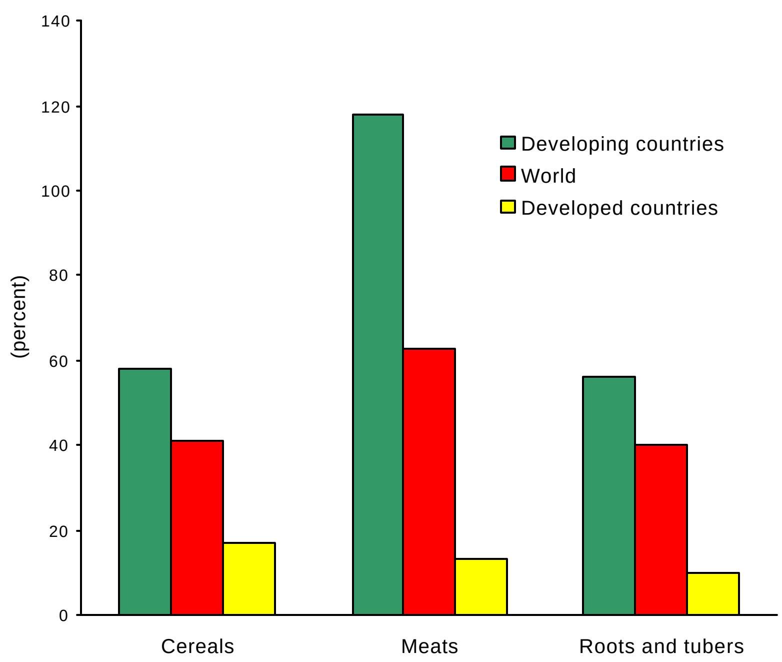
As a result of the projected growth in population and income and the changes in tastes and preferences of consumers described above, most of the increase in demand for the major food commodities is expected to occur in the developing countries. Sub-Saharan Africa is expected to experience the highest percentage increase in demand. Projections of IFPRI IMPACT simulations (Pinstrup-Andersen *et al*., 1997) show that, between 1993 and 2020, the developing countries will account for more than 75% of the increase in global cereal demand, over 90% of the increase in meat demand, and almost 90% of the increase in demand for roots and tubers (Figure 2). Because increases in the demand for livestock products are expected to be substantial, mainly as a result of the effects of urbanization and income growth on patterns of food consumption, the demand for maize (as animal feed) is expected to grow faster than for other cereals. Changes in patterns of consumption will induce changes in patterns of crop production.

Figure 1. Projected average annual income growth rates, 1993-2020.



Source: IFPRI IMPACT simulations.

Figure 2. Increase in total demand for cereals, meats, and roots and tubers, 1993-2020.



Source: IFPRI IMPACT simulations.

However, because of land constraints, expansion of area cultivated will not contribute much to growth in production. Thus, increases in demand will have to be met through agriculture intensification and improvements in crop yields that will have a direct and positive effect on the demand for plant nutrients including P fertilizers.

Cereal production in many countries will be insufficient to meet expected increases in demand. Developing countries as a group are expected to more than double their net imports of cereal. IFPRI IMPACT simulation show that with the exception of Latin America, all major developing regions are projected to increase their net cereal imports (Figure 3). Asia's projected dramatic growth is due to expectations of rapid income growth, despite recent economic and financial problems in some countries of Southeast Asia. It is expected that recovery will occur in 2-5 years and the long-term growth of income in the region will not be affected substantially by these events. International trade of cereals, mainly wheat and maize, will increase substantially in the next 25 years. Trade in rice is expected to remain not significant. The United States and Australia are expected to increase significantly their share in the export market of cereals (mainly wheat and maize) and Eastern Europe and the former Soviet Union could become significant net exporters (Figure 4). Trade of meat products also will increase as a result of the rapid rise in demand in developing countries that is expected to occur in response to growth in population and income, and changes in lifestyles induced by urbanization. Developing countries as a group are expected to increase their net meat imports 20-fold (about 11.5 million tons) in 2020 (Figure 5).

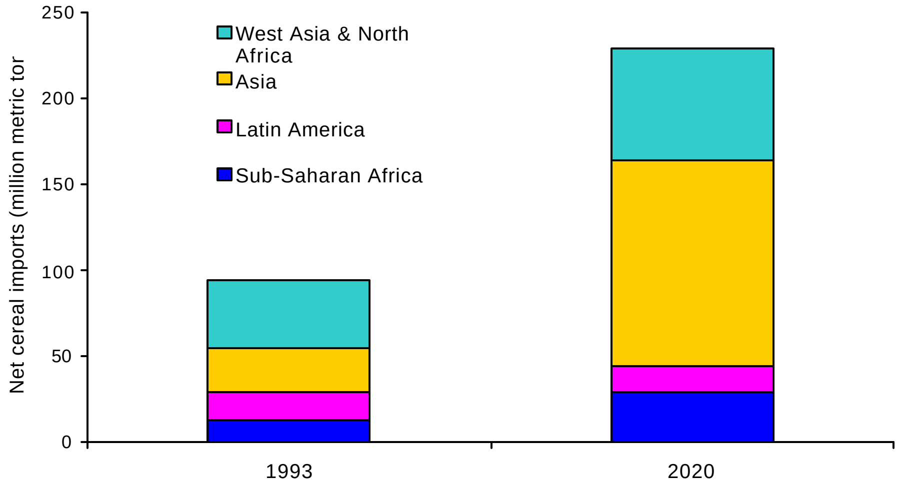
The significant future increases in trade of cereals and meat products have direct consequences on the future demand and trade for fertilizers, in general, and P fertilizers in particular. Net exports of food products imply net exports of plant nutrients from farmers fields in exporting countries. To avoid the depletion of plant nutrients from soils in these countries, nutrients must be replenished mainly by the application of sources of plant nutrients to those soils. In some countries this will require the net import of fertilizers. For instance, higher levels of net exports of cereals from Australia and of meat products from some countries in Latin America are expected to result in increased demand for (and imports of) fertilizers in these countries.

2. Resource Constraints and Agricultural Intensification

Land Constraint—Most of the food demanded by the world's population in the coming decades will be produced on today's arable lands. Although there is no reliable way to predict changes in arable land areas in each country, it is expected that these areas will increase in some countries, in Latin America (Brazil and Argentina) and in Africa (Zambia and Zaire), but will decrease in most countries. Thus, it is expected that gains in arable land will be offset by losses due to land degradation and the conversion of arable land to other uses as a result of urbanization. It is therefore not unreasonable to hold arable land values constant at 1990 levels when land-population ratios are calculated and projected to 2025 (Engelman and LeRoy, 1995).

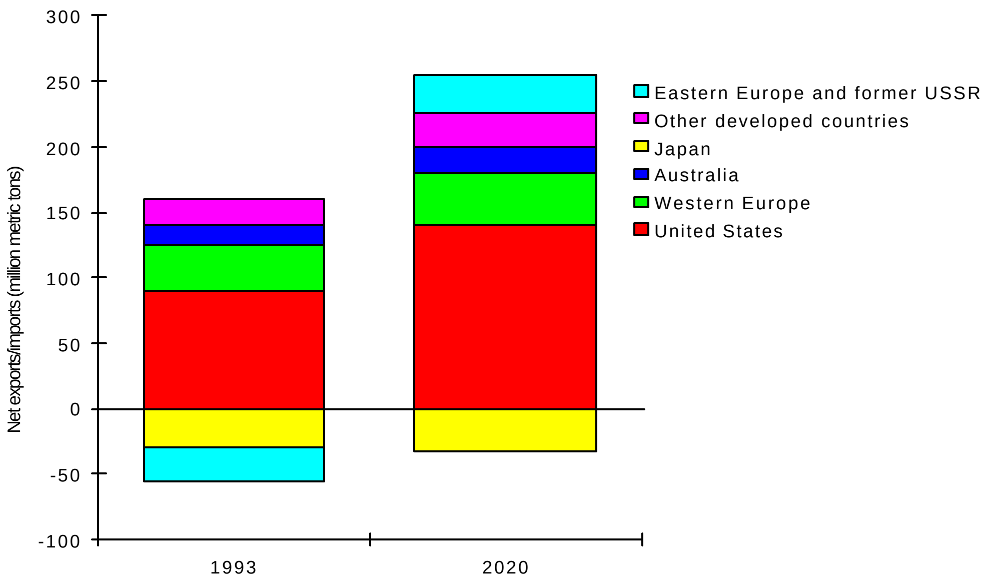
Estimates of average arable land per person presented in Table 1 by regions and subregions show clearly that arable land per person declined substantially in all regions of East Asia as a whole, especially in China and South Asia, between 1961 and 1990. These trends are expected to continue during 1990-2025 and show that land scarcity will continue to be an increasingly important determinant of agricultural intensification as the key for increasing food production to meet the growing demand for food in the future. The need for agricultural intensification as a result of land scarcity will become especially important in East and South Asia and in most of

Figure 3. Net cereal imports of major developing regions, 1993 and 2020.



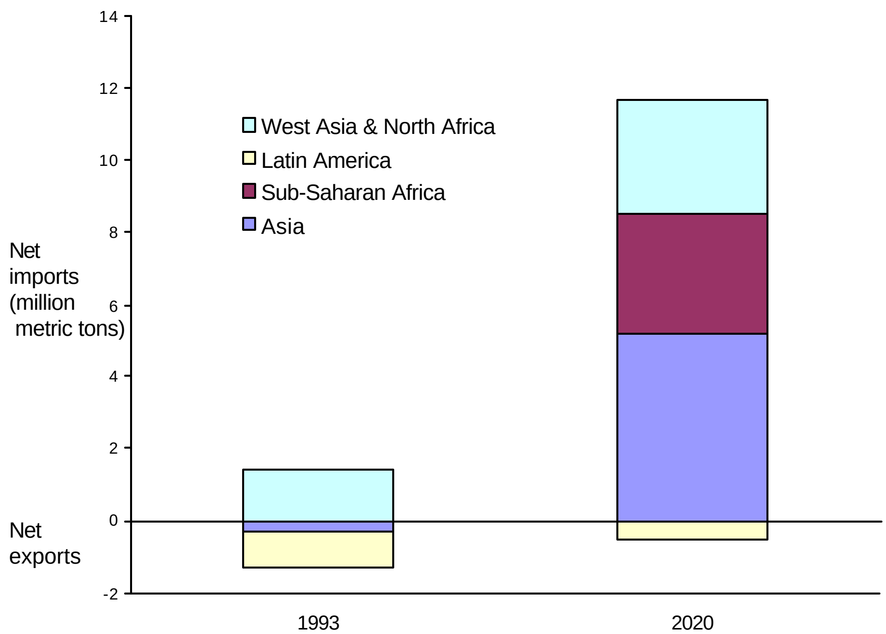
Source: IFPRI IMPACT simulations.

Figure 4. Net cereal trade of developed countries, 1993 and 2020.



Source: IFPRI IMPACT simulations.

Figure 5. Net trade in meat by major developing regions, 1993 and 2020.



Source: IFPRI IMPACT simulations.

Table 1. Availability of Arable Land Per Person, 1961, 1990, and 2025.

Region/Subregions[1]	Average Land Per Person(ha) 1961	1990	2025[3]	Average Annual Rate[2] of Growth (%) 1961-90	1990-2025
North America	1.14	0.84	0.63	-1.01	-0.82
Western Europe	0.32	0.25	0.24	-0.88	-0.04
Eastern Europe	0.51	0.39	0.38	-0.89	-0.09
Eurasia	1.12	0.79	0.73	-1.15	-0.26
Africa:					
Sub-Saharan Africa	0.56	0.29	0.12	-2.17	-2.66
South Africa	0.74	0.36	0.19	-2.45	-1.85
North Africa	0.41	0.23	0.13	-2.00	-1.63
Latin America:					
Central America	0.54	0.27	0.15	-2.36	-1.60
South America	0.47	0.39	0.25	-0.64	-1.30
Asia:					
West Asia	0.72	0.31	0.15	-2.79	-2.15
South Asia-India	0.36	0.20	0.12	-1.98	-1.40
South Asia-Other Countries	0.31	0.16	0.08	-2.12	-2.05
South Asia-Total	0.35	0.19	0.11	-2.04	-1.61
East Asia-China	0.16	0.08	0.06	-2.15	-0.82
East Asia-Other Countries	0.17	0.13	0.09	-0.95	-1.04
East Asia-Total	0.17	0.10	0.07	-1.84	-0.88
Oceania	2.13	2.07	1.36	-1.10	-1.19

[1]See Appendix for classification of countries by region.
[2]Constant exponential rate of growth.
[3]Based on United Nations medium projection for population growth.

sub-Saharan Africa. Increases in land productivity through agricultural intensification are expected to occur as a result of the development and/or adoption of yield-enhancing technologies that will be more demanding of plant nutrients. The additional nutrient requirements will be partially provided by improvements in nutrient recycling and in the efficiency of use of nutrient applied, but most of the additional nutrient requirements will have to come from additional applications of external sources of plant nutrients, mainly, mineral fertilizers. Because phosphorus cannot be fixed by plants as nitrogen is fixed by legumes, the additional demand for P fertilizers is expected to be closely related to agricultural intensification and the initial content or endowment of P in the soil that is, or will become, available to plants with time.

As arable land becomes increasingly scarce, relative prices and economic circumstances will induce the development and adoption of technologies that increase yields but also maintain the quality of the limited land resources in terms of long-term productivity. Under these circumstances, the demand for mineral fertilizers must be viewed in the context of integrated nutrient management and crop rotations and cropping systems that are established with the objective of increasing land productivity while maintaining soils without deficiencies in plant nutrients, including micronutrients, and with good physical structure and biological quality (Syers, 1997).

Maps presented in Figure 6 show that arable land scarcity will increase substantially more in some countries as a result of the mismatch between availability of arable land and demographic trends. For instance, nine countries—India, China, Pakistan, Bangladesh, Mexico, Iran, Vietnam, Ethiopia, and Egypt—have very limited potential to expand arable land but as a group account for half of the world's population growth. In contrast, four countries—Brazil, Argentina, Zaire, and Zambia—have significant potential to farm more land but as a group account for only slightly more than 5% of world population growth. Hence, differences among countries in current levels of arable land per person and in the rates of growth in population will also cause disparities in the rates of agricultural intensification among countries.

Water Constraint—As a result of population growth, fresh water has become increasingly less available to satisfy human needs. Water is essential to social and economic development and for agriculture and the production of food, and the conservation of biodiversity and the environment. Globally, agriculture accounts for about 69% of all the water use. The quantity of fresh water that is continually renewed through the global water cycle is a finite natural resource (Engelman and LeRoy, 1993).

Estimates of average availability of annual renewable fresh water per person are presented in Table 2. These estimates show that there is considerable disparity in water availability among regions and subregions. Water is and will continue to be an increasingly critical constraint in much of Africa and in West and South Asia. In North America, Eurasia, South America, and Oceania, the average availability of fresh water per person is expected to continue to be abundant in 2025. Maps shown in Figure 7 show the variability in average water availability among countries and that more countries will become water-scarce countries (less than 1,000 cubic meters per person per year) or will fall in the category of water stress countries (1667 cubic meters per person per year). It is projected that between 1990 and 2025 the number of people living in water-scarce countries will increase from about 131 million to more than 817 million (Gardner-Outlaw and Engelman, 1997).

Table 2. Availability of Renewable Fresh Water per Person per Year, 1961, 1990, and 2025.

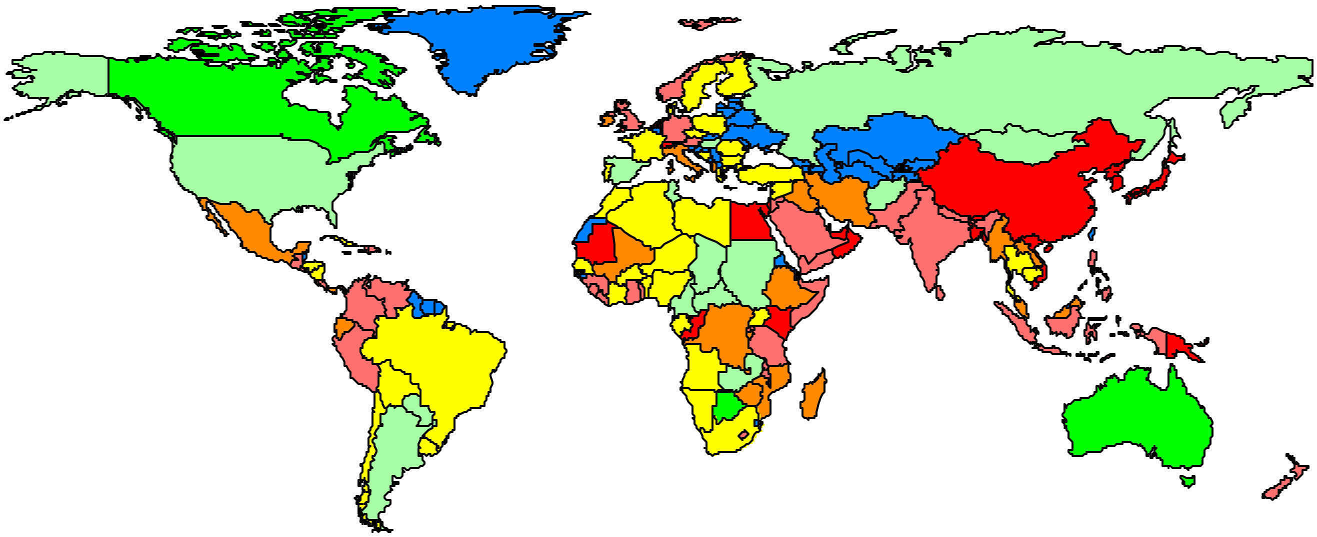
Region/Subregions[1]	Fresh Water Per Person (000 cubic meters) 1961	1990	2025[3]	Average Annual Rate[2] of Growth (%) 1961-90	1990-2025
North America	27.09	19.37	14.56	-1.12	-0.82
Western Europe	6.11	5.27	5.21	-0.50	-0.03
Eastern Europe	9.67	7.85	7.61	-0.70	-0.09
Eurasia	25.46	18.96	17.31	-0.98	-0.26
Africa:					
Sub-Saharan Africa	21.77	9.52	3.73	-2.76	-2.68
South Africa	2.87	1.35	0.70	-2.52	-1.86
North Africa	2.03	0.96	0.54	-2.50	-1.64
Latin America:					
Central America	18.11	8.13	4.66	-2.67	-1.59
South America	81.25	40.75	25.82	-2.30	-1.30
Asia:					
West Asia	6.24	2.51	1.18	-3.04	-2.15
South Asia-India	4.71	2.45	1.50	-2.18	-1.41
South Asia-Other Countries	27.68	3.13	6.36	-2.49	-2.07
South Asia-Total	10.65	5.40	3.08	-2.26	-1.61
East Asia-China	4.26	2.42	1.83	-1.88	-0.80
East Asia-Other Countries	16.01	9.04	6.28	-1.91	-1.04
East Asia-Total	8.21	4.66	3.42	-1.89	-0.88
Oceania	105.78	63.98	42.13	-1.68	-1.19

[1]See Appendix for classification of countries by region.
[2]Constant exponential rate of growth.
[3]Based on United Nations medium projection for population growth.

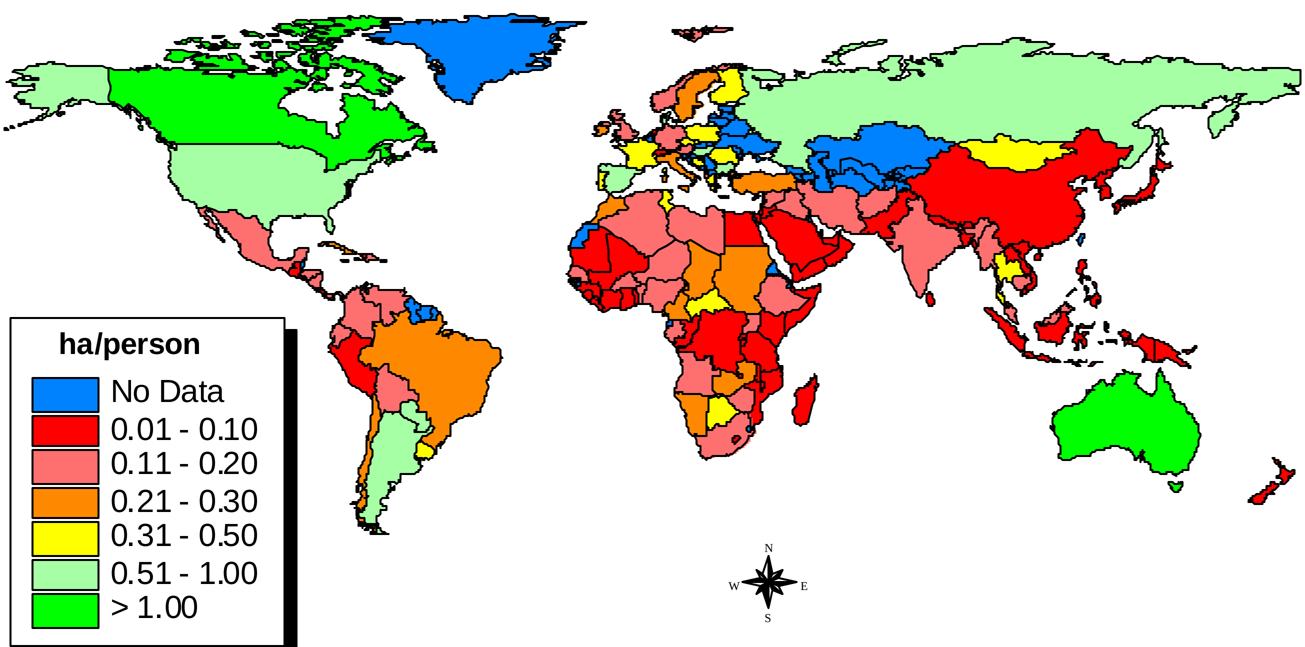
An essential requirement for sustainable development is that natural resources are used in a manner that their availability will not be more limited to future generations. The expected increased scarcities in land and water that have been described above indicate that technologies to increase the productivities of land and water resources on a sustainable basis should be in greater demand in the future. These technologies will have to include improvements in the management of plant nutrients, probably involving more recycling and increased efficiency in the use of applied nutrients. Also, the addition and management of micronutrients and issues on the nature of interactions of external sources of plant nutrients with water quality, soil biology, and overall soil fertility and conservation will provide new challenges and opportunities for technological improvements.

Land and water scarcity and technological improvements—induced by changes in resource endowments and relative prices—should be the main drivers of agricultural intensification during the next 25-30 years on the side of food production and supply. Increases in the demand for plant nutrients and P fertilizers are expected to occur more in regions and countries where there is greater potential for expansion of agricultural intensification. Thus, the changing

FIGURE 6
Availability of Arable Land per Person in Hectares (Year 1990)

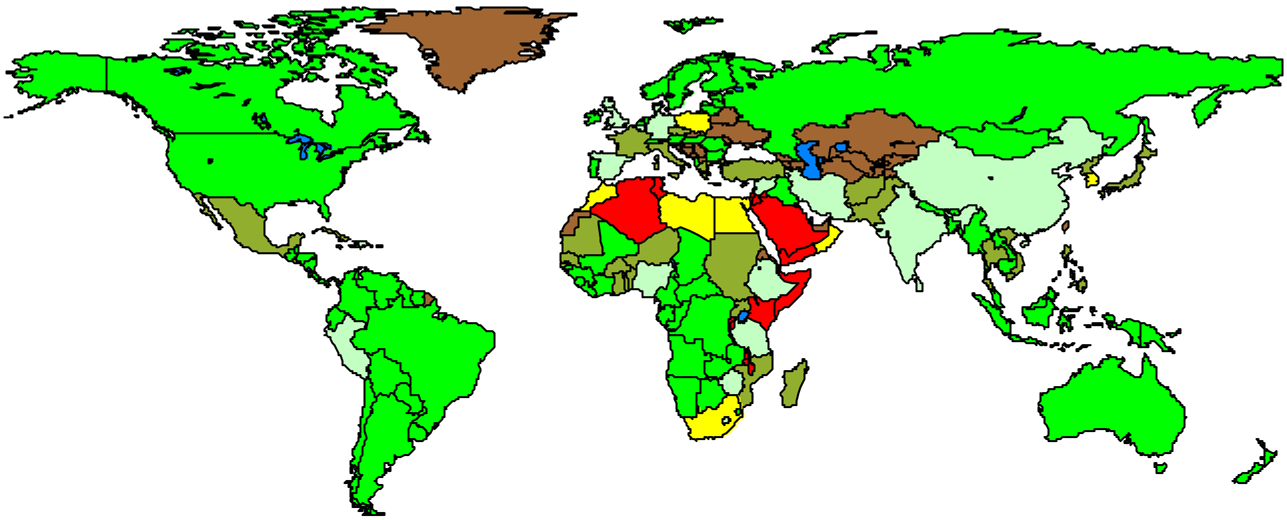


Availability of Arable Land per Person in Hectares (Year 2025 - Medium Population Projection)

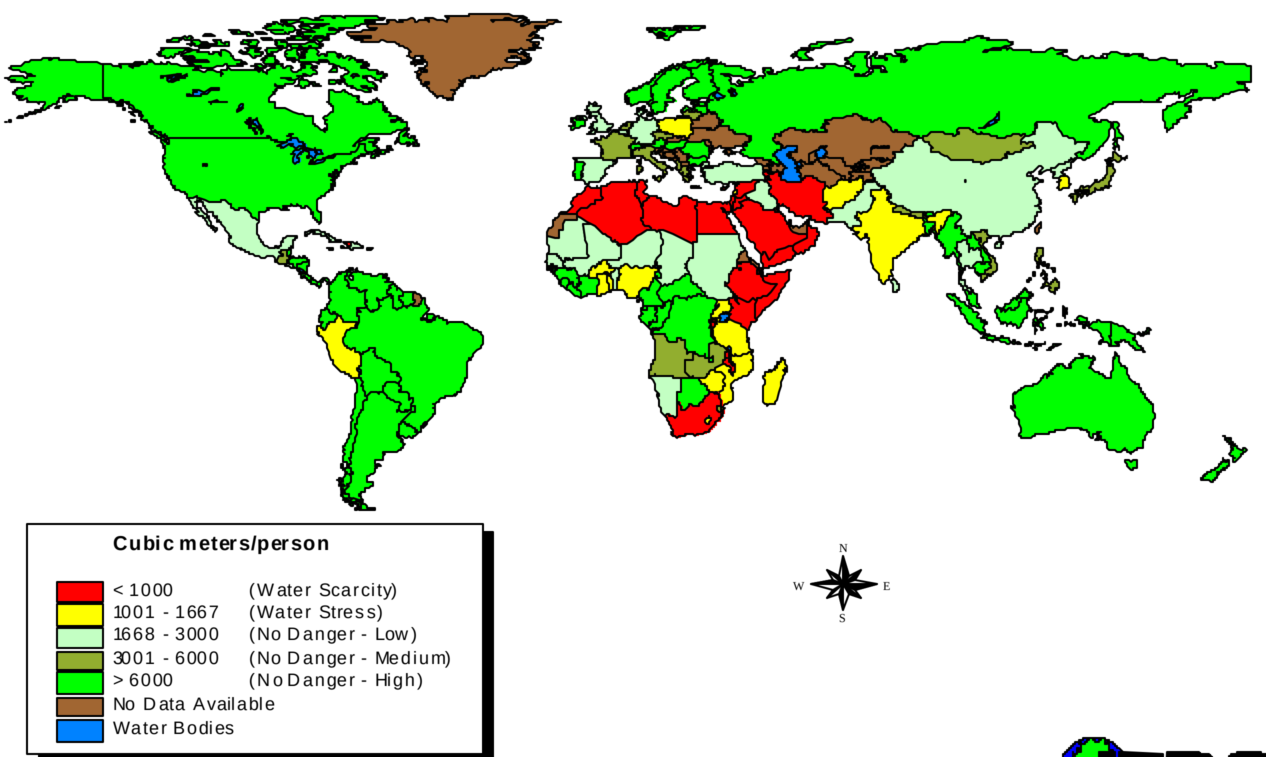


Data Source: Population Action International

FIGURE 7
Annual Water Availability per Person (Year - 1990)



Projected Annual Water Availability per Person (Year - 2025/Medium Projection)



Data Source: Population Action International biophysical and technological circumstances should induce a rapid growth in demand for nutrients and P fertilizers in regions and countries where current levels of use are low, such as sub-Saharan Africa. This growth, however, will be realized only if a conducive policy environment is established to insure the sustainable profitability of agricultural intensification.

3. Technological Innovations

There is no doubt that in the last three decades modern technologies such as hybrid seeds and synthetic fertilizers have had major impacts on improving farm productivity and economic development by inducing the growth of new businesses and infrastructure. Today's emerging technologies, most importantly, biotechnology and precision farming, are ushering in a new era that will impact farmers' day-to-day operations, continue to improve farm productivity, and transform the agribusiness infrastructure.

The initial primary emphasis of biotechnology has been on increased productivity through the genetic modification of soybean, cotton, and maize seeds to provide increased insect and herbicide resistance. There is also considerable research activity in developing hybrids of rice, maize, sorghum and wheat that are tolerant of high levels of solubilized aluminum in acid soils. Another area receiving considerable attention is genetic modification of input traits to improve the quality of crop outputs such as increased nutritional value, virus resistance, and handling characteristics (Thayer, 1997).

The biotechnologies currently being moved into the commercial sector (*Bt* cotton, *Bt* corn, Roundup-ready soybean) should reduce input costs for herbicides and pesticides but are not expected to negatively affect fertilizer use. However, the success of these genetically engineered seeds will likely increase the possibility for input traits that could reduce the demand for some fertilizers in the future. For example, the development of varieties that included traits which increased nutrient use efficiency or incorporated the ability to biologically fix N could significantly impact fertilizer consumption, including phosphate fertilizers.

In the long term, biotechnology may affect the overall production of food crops. Farmers who see the potential for greater profits from a new high-value specialty crop may focus their efforts in those areas. If this occurs, the fertilizer industry may see a shift in the type of products it provides.

In the foreseeable future, the impact on phosphate fertilizer use is more likely to be felt from precision agriculture. Precision farming focuses on improving the optimization of agricultural inputs use. Precision agriculture technologies allow variable rate fertilizer application within a field so that nutrients are applied based on crop needs and the available nutrient reserve present in the soil. Due to previous fertilization practices, many of the soils of North America and Western Europe have high P fertility levels; thus, they only require maintenance doses of P to replace the P removed in the harvested crop. By recognizing and responding to this situation, precision agriculture can increase nutrient use efficiencies and minimize nutrient losses. However, due to the need for high initial capital investment, precision agriculture is currently targeted to large farming operations.

Another technology that has the potential to increase both nutrient and water use efficiency while helping to maintain the environmental integrity of the natural resources (soil and water) is fertigation. This technology is playing an increasingly important role in meeting the need for increased agricultural productivity in semiarid regions where a constraint for water availability is often accompanied by low soil fertility and land scarcity.

The effect of fertigation technology will be more on the product mix than on fertilizer consumption. Urea is well suited to fertigation, but traditional phosphate fertilizers tend to precipitate in these systems, with the probability of precipitation increasing substantially when phosphate fertilizers applied contain a large proportion of calcium and/or magnesium. Increased use of fertigation (and hydroponics) would require that more water-soluble products be available. Two products that have provided good results are orthophosphoric acid and urea phosphate.

The primary disadvantages of fertigation, particularly drip irrigation, are the initial high investment, more expensive inputs, and the skilled labor required for maintaining the system. At present, fertigation is best suited for high value crops, but in the future, water scarcity may be the driving force for increased use. Fertigation has played a major role in Israel's intensive modern agricultural system and is expected to increase in importance in cultivated lands subject to water scarcity such as the vast areas of cultivated lands in India (Figure 7).

Precision farming combined with biotechnology will result in a growing trend to prescription farming that will affect farmers' day-to-day operations. These new technologies have already promoted consolidation in the agribusiness infrastructure with the merger of biotechnology firms, seed companies, and agricultural-chemical companies. Driven by economics of scale and profitability, these consolidations will continue and will eventually lead to greater vertical integration as biotech/seed/ag-chemical companies form alliances or merge with downstream companies. An objective of this vertical integration will be to capture a greater portion of proprietary knowledge, particularly biotechnology-generated, value-added crop/output characteristics.

Dramatic changes will occur in the agriculture production/distribution system within the next 25 years. Information technology will be critical not only for improving efficiencies but also for providing a competitive advantage. Due to this increased value of information and the increasing role of the private sector in providing it, the issue of proprietary nature of and access to information is becoming more complex. Since information provides a competitive advantage, the exchange of some information may be reduced. As the use of precision farming grows, it will increase the complexity of decisionmaking and expand the need for more sophisticated information and expertise. The issue of who owns the information will become more and more important but less clear and difficult to define. For example, who owns site-specific soil characterization data—the grower who paid for the information or the service company who gathered the information? If industrial growers have the potential to obtain superior information, how would the traditional farmer gain access to information and remain competitive? The concept of intellectual property rights must consider these questions. Proprietary knowledge must also be evaluated in the context of global markets and multinational business firms and the shrinking role of the public sector in research and development and information dissemination and the increasing importance of information as a source of strategic competitive advantage (Boehlje, 1996; Shimoda, 1997).

4. Environmental Concerns

Agricultural intensification in industrialized countries has produced great economic and social benefits, but there have also been environmental costs. Current environmental concerns of most relevance to fertilizer use are centered on atmospheric emissions of ammonia and nitrogen oxide gases, nitrate pollution of groundwater and surface runoff of nutrients, particularly phosphorus. While excess phosphate is not directly toxic to humans or plants, too little or too much phosphate can produce severe environmental impacts in the form of land degradation or eutrophication, respectively.

Many highly weathered soils in the warm humid and subhumid regions of the world have low levels of soil P available to support plant growth in cultivated systems. In natural ecosystems, the recycling of P contained in the biomass, soil organic matter and decaying residue is sufficient to support plant growth as long as the system remains undisturbed. However, once such land is cleared for cultivation, losses of P via soil erosion, runoff water, and biomass removal can be substantial. Over the course of a few years, plant-available P declines rapidly. If it is not replenished through external inputs (organic or inorganic), yields decrease dramatically and any regrowth of natural vegetation will be sparse.

This situation provides a foundation for land degradation, because plant growth is minimal, erosion increases, water-holding capacity decreases, and degradation accelerates. Estimates indicate that 1-2 billion hectares of arable land in the world are deficient in P. Much of this land is in poor countries where subsistence farmers have little access to phosphate fertilizers (organic or inorganic). Without judicious external inputs of phosphate and other nutrients, these lands cannot be productive. Although these lands represent a potential market for greatly increased fertilizer use, several constraints to economic development may prevent this potential from being realized in the next 25-30 years.

The detrimental environmental effects of too much phosphate are quite different and usually result from improper management practices. Most of the water-soluble P of phosphate fertilizers is converted to less soluble immobile forms upon addition to the soil. Phosphate is primarily removed from arable land as harvested output or through soil erosion. While small amounts of phosphate may be leached from the soil, erosion can carry substantial amounts of phosphate into surface waters. The availability of phosphate usually restricts plant growth in fresh water, but its addition through erosion can result in plant proliferation and eutrophication which often adversely affects water ecology, quality, and use.

Phosphorus from both point and nonpoint sources are contributing to eutrophication problems. Pollution from point sources is relatively easy to identify and control as compared to nonpoint sources, and considerable advances in reducing P leakage from point source pollution have occurred in industrialized countries. Nonpoint sources of P are the major contributors to eutrophication in many regions and consist primarily of runoff water and eroded sediments from soils within an affected watershed. In many countries, annual application of phosphate to intensively managed agricultural soils has substantially increased the phosphate content of surface soils; therefore, the impact of runoff and eroded sediments on stream phosphate loading has increased. Within a watershed, phosphate losses can be increased by human activity including tillage, timber harvesting, and application of phosphate as mineral fertilizers or organic sources such as animal manure. Watersheds containing agricultural areas that received phosphate applications as mineral fertilizers or organic manure have been shown to carry much higher phosphate loads than streams draining relatively undisturbed forests and natural grasslands (Smith et al., 1991).

Environmental problems are also associated with the production and use of phosphate fertilizers because raw material from different phosphate deposits contains varying low concentrations of heavy metals that are potentially harmful. These metals including arsenic, cadmium, chromium, lead, mercury, and uranium are the focus of increased public concern both from the standpoint of potential environmental contamination from the phosphogypsum waste by-product to the possibility of potential contamination of the food chain from the use of phosphate fertilizers. In industrialized countries, these concerns have already translated into regulations that have affected global trade of raw materials and in some cases increased production costs. Additional concerns or regulations would force the fertilizer industry to look for economical means of providing phosphate products essentially free of these toxic metals. To date, unfavorable economic considerations have prevented the adoption of technologies that remove cadmium and uranium from phosphate rock and/or phosphoric acid (Schultz et al., 1992). New technologies utilizing ion-exchange resins and/or semi-permeable membranes may provide economic means of removing metal contaminants from phosphoric acid in the future.

Presently, improved agricultural practices are providing some answers to environmental problems associated with fertilizer use. Precision agriculture technologies as well as the use of controlled-released fertilizers and enzyme inhibitors can increase nutrient use efficiencies. The use of cover crops, minimum tillage, and grass strips around the perimeter of fields are helping to reduce the loss of nutrients, particularly P, to nearby streams and lakes.

In general, the control of eutrophication in many streams and lakes can be accomplished by better management techniques, whereas overcoming the long-term effect of the low use of nutrients and the resulting land degradation will be much more difficult. While environmental concerns are not expected to affect global demand in phosphate fertilizers, they will contribute to reduced demand in Western Europe. These concerns may also result in international regulations that may affect fertilizer prices; thereby, adversely affecting developing countries where there is tremendous need for increased phosphate fertilizer use.

D. The Potential Future Demand for P Fertilizers

1. Demand Projections to 2025

Estimates of average rates of application of major plant nutrients NPK ($N + P_2O_5 + K_2O$) by region/subregion presented in Table 3 show that despite significant growth between 1961 to 1990, there is considerable potential for future growth in most developing regions and countries, especially in sub-Saharan Africa, South America, and West and South Asia.

Table 3. Average Use of NPK (N + P_2O_5 + K_2O), 1961 and 1990.

Region/Subregions[1]	Average NPK Use (NPK kg/ha) 1961	1990	Average Annual Rate[2] of Change (ha) 1961-90
North America	36.0	89.28	3.03
Western Europe	122.0	239.24	2.25
Eastern Europe	49.5	141.83	3.51
Eurasia	12.0	96.45	6.95
Africa:			
Sub-Saharan Africa	1.4	9.39	6.34
South Africa	18.0	64.04	4.23
North Africa	15.5	69.11	4.98
Latin America:			
Central America	10.3	78.52	6.77
South America	10.3	56.77	5.69
Asia:			
West Asia	3.4	73.42	10.24
South Asia-India	2.2	75.87	11.80
South Asia-Other Countries	6.3	64.24	7.74
South Asia-Total	3.1	73.09	10.53
East Asia-China	6.0	289.72	12.92
East Asia-Other Countries	67.7	283.24	5.94
East Asia-Total	20.9	286.88	8.73
Oceania	21.6	32.10	1.32

[1]See Appendix for classification of countries by region.
[2]Constant exponential rate of growth.

Estimates of potential future demand for P fertilizers in terms of P_2O_5 projected by regions and subregions are presented in Table 4. The year 1990 was used as a base year because during 1989/90-1994/95 fertilizer use decreased substantially as a result of abnormal circumstances during those years, but it appears to be recovering in the later 1990s. During the 1990-2025 period, the demand for P_2O_5 is expected to grow at a constant and continuous exponential growth rate of 1.34% per year or at a growth rate of r = 0.0134. The growth rate r is calculated by the equation

$$r = \ln(X_n / X_1) / n \qquad (4)$$

where X_n and X_1 are the last and first observations in the period, n is the number of years in the period and ln is the natural logarithm operator. Although most of the projected increases in global fertilizer use are expected to occur after the year 2000 (Bumb and Baanante, 1996), constant rates of growth are calculated for the purpose of estimating long-term demand projections.

Rates of growth of fertilizer demand during 1990-2025 are expected to be substantially lower than those experienced during the 1960-1990 period. Western Europe and Eurasia are expected to experience negative rates of growth in demand for fertilizers as a result of environmental

Table 4. Projections of Demand for P Fertilizer to 2025.

Region/Subregions[1]	P_2O_5 Consumption 1990 (000 mt)	Average Annual Rate of Growth (%)[2]	P_2O_5 Projected Demand 2025 (000 mt)	Increase in Demand 1990-2025 (000 mt)
North America	4,600	0.89	6,272	1,672
Western Europe	5,100	-0.81	3,842	-1,258
Eastern Europe	2,300	0.28	2,535	235
Eurasia	8,200	-0.53	6,818	-1,382
Africa:				
Sub-Saharan Africa	400	3.05	1,165	765
South Africa	300	2.31	674	374
North Africa	400	3.05	1,165	765
Latin America:				
Central America	500	2.31	1,122	622
South America	1,900	2.48	4,528	2,628
Asia:				
West Asia	1,500	2.63	3,763	2,263
South Asia	3,700	2.77	9,764	6,064
East Asia	7,500	2.44	17,625	10,125
Oceania	1,100	1.03	1,580	480
World	37,500	1.34	60,852	23,353

[1]See Appendix for classification of countries by region.
[2] Constant exponential rate of growth.

regulations in Western Europe and due to economic reform and political instability in Eurasia (Bumb and Baanante, 1996). In Eastern Europe and Eurasia, fertilizer use is expected to decrease during most of the 1990s and then have a slow to moderate recovery in the late 1990s and early years of the 21st Century. North America and Oceania are expected to experience moderate average rates of growth of about 0.9% to 1% per year due mainly to improved prospects for exports of cereals. The demand for P fertilizers in Asia, Africa, and Latin America is projected to grow by 2% to 3% per year. In absolute amounts, Asia is expected to experience the largest increase in demand for P fertilizers—an increase of about 18.2 million tons of P_2O_5 between 1990 and 2025 with most of this increase or about 10.1 million tons to take place in East Asia. In relative terms, however, increase in the demand for P fertilizers will be highest in South Saharan Africa and North Africa where the demand for P fertilizers is projected to increase at an average rate of about 3% per year. The relatively high rate of growth that is projected for sub-Saharan Africa is mainly due to the initial low levels of P fertilizers used in 1990, less than 10 kg of P_2O_5 per hectare.

In Central and South America, the demand for P fertilizers is expected to increase at rates of growth of about 2.3% and 2.5% per year. In the next 25-30 years, Asia, Latin America, and Africa will increase their shares in the total demand and market for P fertilizers at the expense of declines in the market shares of Western Europe, Eurasia, and Eastern Europe, and, to a lesser degree, in the shares of North America and Oceania. These shifts in market shares and the associated changes in the expansion of demand for P fertilizers among regions and countries will result in substantial increases in the international trade of P fertilizers from producing countries located mainly in North Africa, North America, Western Europe, and Eurasia to countries in Asia, Oceania, and Latin America.

It is important to note that any projection made over a time horizon of several decades should always be treated with caution. These projections are useful to better evaluate if the potential capacity of the fertilizer industry and the raw material reserves of phosphate rock are suitable to meet the future demand even if this demand were to be 10% or 20% higher than it is estimated here. These estimates are also useful to assess implications for international trade and the long-term conservation of land resources of the environment. The net outflow of P nutrient, that is, a negative P nutrient balance associated with nutrient mining cannot be sustained for many years and can have serious consequences to the conservation of the land resource base, mainly as a result of soil erosion, decline in soil fertility, and ultimately, land degradation.

2. Explaining Changes in the Demand for P Fertilizers

An attempt is made here to explain the nature and magnitude of the effects of some key variables on the demand for P fertilizers by using cross-sectional 1990 country-level data to estimate a function of the use of P_2O_5 per hectare. Because the availability of arable land is not expected to change significantly in most countries, variables and factors that explain changes in the use of P_2O_5 per hectare are, in fact, explaining changes in the demand for P fertilizers. The following two models were estimated using ordinary least-square procedures.

Linear Model:

$$Q_p = \alpha_o + \sum_{i=1}^{5} \alpha_i D_i + \beta_1 L_c + \beta_2 W_c + \varepsilon \qquad (5)$$

Logarithmic Model:

$$\ln Q_p = A_o + \sum_{i=1}^{5} A_i D_i + \beta_1 \ln L_c + \beta_2 \ln W_c + \varepsilon \qquad (6)$$

In these models, the average quantity of P_2O_5 used per hectare by country , Q_p, is assumed to be determined by (a) the availability of arable land per person L_c and the availability of fresh water per person W_c as the main sources of agricultural intensification caused by resource scarcity and (b) a set of 0-1 dummy variables D_i to account for differences among groups of countries that are present as a result of geographic location and differences in agricultural technology, agroecological circumstances, and the policy environment. Hence, in these models, the following independent variables were included:

D_1 = 1 for countries in sub-Saharan Africa and 0 otherwise;
D_2 = 1 for countries in North Africa and Middle East and 0 otherwise;
D_3 = 1 for countries in Central and South America and 0 otherwise;
D_4 = 1 for countries in Asia and 0 otherwise;
D_5 = 1 for countries in Oceania and 0 otherwise;
L_c = arable land per person in hectares; and
W_c = fresh water available per person in thousands of cubic meters.

ln is the natural logarithm operator and e is a random error.

Eighty countries were included as observations to estimate these two models. Countries from Eastern Europe, Eurasia, China, and others that have central planned economies or face special political circumstances were not included.

Coefficient estimates of the linear and logarithmic models are presented in Table 5. These estimates show that land scarcity is a key determinant of agricultural intensification and the associated intensity in use of P fertilizers. The coefficients of the variable arable land per person (L_c) are statistically significant at the 0.01 level of significance and show that on the average and holding other factors constant, the use of P_2O_5 per hectare increases by about 0.5% as a result of a 1% decrease in the availability of arable land per person. This coefficient estimate also implies that if the area of arable land and other factors are held constant, a 2% increase in population would be associated with a 1% increase in the use of P_2O_5 per hectare. The negative sign of the coefficient estimates of the variable available fresh water per person (W_c) also show that water scarcity contributes to agricultural intensification. These coefficients, however, are not statistically significant. This is not unexpected and is explained by the fact that water availability can have a positive or a negative effect on the intensity of plant nutrient use. Water and plant nutrients applied behave as complementary inputs within some range of quantities used and as substitutes within another range of quantitative combinations. The efficiency and effectiveness of plant nutrients on crop production decline at very low or very high levels of water use. Thus, there are limitations in these two models in regard to the specification of the water variable.

Coefficient estimates of the discrete 0-1 variables indicate the influence on P_2O_5 use of all variables, other than land and water scarcity, that are associated with the geographic location and other common characteristics of the countries included in each country-group. Coefficient estimates of these variables are also presented in Table 5 and show that with respect to the use of P_2O_5/ha in Western Europe and North America, these variables explain significant lower levels of use of P_2O_5/ha for sub-Saharan Africa (D_1) and somewhat lower levels of use of P_2O_5/ha in countries of North Africa and the Middle East (D_2), Central and South America (D_3) and in Asia (D_4) and somewhat higher levels in countries of Oceania (D_5). This last result may be because land is and has been for some time an important constraint and a source of agricultural intensification in Western Europe, but it is not yet a critical constraint in Australia and New Zealand.

Although in these models about 83% and 66% of the variability in use of P_2O_5/ha is explained by the independent variables, the two models have limitations that should be indicated. The estimated models have limitations mainly because of (a) the lack of proper specification of economic variables to account for the policy environment, and (b) the use of only cross-sectional data rather than time-series and cross-sectional data which should be more proper for this type of analysis.

Table 5. Coefficient Estimates and Statistics of Linear and Logarithmic Models Explaining the Intensity of Use of P Fertilizers.

Variables	Coefficient Estimates[1] Linear Model	Logarithmic Model
Dependent Variable:		
Q_p — Quantity of P_2O_5 per hectare		
Independent Variables:		
Intercept[2]	58.43**	4.54**
	(3.05)	(0.99)
Discrete 0-1 Variables:		
D_1 — Sub-Saharan Africa	-47.34**	-3.65**
	(3.11)	(0.38)
D_2 — North Africa and Middle East	-28.55**	-1.01*
	(4.18)	(0.53)
D_3 — Central and South America	-33.23**	-1.35*
	(3.42)	(0.43)
D_4 — Asia	-31.89**	-1.16*
	(4.46)	(0.57)
D_5 — Oceania	32.08**	0.48
	(6.55)	(0.76)
Continuous Variables:		
L_c — Arable land per person in hectares.	-24.27**	-0.49**
	(3.05)	(0.20)
W_c — Fresh water per person (1000 cubic meters)	-0.022	-0.15
	(0.021)	(0.10)
R-Square	0.83	0.66

[1]Standard errors are in parentheses.
[2]Western Europe and North America as a basis.
*Statistically significant at 0.05 level.
**Statistically significant at 0.01 level.

E. Future Challenges

Projected growth in demand for food and agricultural products will continue to be driven mainly by the growth in population and income in the developing countries. The additional demand for food will put increased pressure on limited resources of arable land and water. Because opportunities for net expansion of arable land are very limited or not present, agricultural intensification will be required to meet the expected growth in demand for food. The goals of food security, economic development, and social and political stability cannot be achieved without the effective and efficient supply of food products demanded by a growing population. In addition to the direct and positive effects that agricultural intensification has on the demand for P fertilizers and plant nutrients in general, it imposes new challenges to scientists, policymakers, and farmers.

Challenges for innovation in technology and in policy design must be addressed and confronted by scientists and policymakers at national and international levels so that agricultural intensification can increase food production on a sustainable basis while conserving the resource base and protecting the environment. Addressing these challenges properly requires the use of a comprehensive systems approach to food and agricultural production so that all interactions and linkages with the resource base, factors of production, and surrounding ecosystems at the local and global environment are established and understood. This approach will facilitate (a) the identification of specific gaps and need for technology improvements, and (b) the evaluation of new technologies in terms of economic, social and environmental benefits, and costs.

A key challenge of agricultural intensification and resource scarcity in the 21^{st} century will continue to be the development of improved technologies to increase the efficiency and effectiveness of integrated nutrient and pest control management on a sustainable basis. These technologies should include the more intensive recycling of plant nutrients, increased use of biological means to fix nutrients and to control pests, and the use of more efficient and "clean" external sources of plant nutrients. Because projected population growth will also result in the increased need for recycling of urban and industrial wastes, technologies to recycle some of these wastes as sources of nutrients for crop production on scarce land resources in an environmentally sound basis will be highly beneficial and will represent a win-win solution to the need for increased productivity and environmental protection (Hedley and Sharpley, 1998).

Technologies and management practices affecting land and water management such as no-till agriculture and drip irrigation are already being adopted in some countries in response to the scarcity of water and land resources and concerns about soil conservation and the environment. All of these technologies should be developed in conjunction with technical innovation in biotechnology and with the objective of conserving land and water resources.

Breakthroughs in biotechnology that will occur in the future could be the dominant sources of change in regard to agricultural intensification. Improvements in biotechnology will include efforts to (a) increase the productivity of land and water resources and the efficiency in use of plant nutrients, and (b) to improve the biological control of pests and diseases of crops and the uptake from the soil of micronutrients that are key for human nutrition.

It is important to emphasize that in the future the world will be characterized by a more interdependent global economy with increased trade in agricultural products, fertilizers, and all other industrial products and raw materials. In such a world, the design of sound economic policies to promote open competitive markets and freer trade will be crucial for food security, resource conservation and economic development. Trade of P fertilizers in the future will increase almost in the same proportion as the growth in demand. International agreements for trade that are expected to become effective early in the 21^{st} century will affect competition and some patterns of trade.

Finally, global and national concerns about the environment will continue to affect the design and implementation of public policy. As resource scarcity becomes more evident and acute, environmental concerns will induce policymakers to design and implement policies that will attempt to price and internalize some of the environmental costs and benefits of agricultural production technologies and practices. These policies and some possible regulations will be established to protect the resource base and environment and as part of international agreements.

Continuous effort in research and development work will be required to address and confront these challenges. Technological improvements and innovation in policy design and implementation will be achieved only through continuous and persistent efforts in research and development work that is relevant to meet these challenges.

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Appendix: Regional Classification of Countries

North America	Western Europe	Eastern Europe	Former Soviet Union	Oceania	Africa	Latin America	Asia
Canada	Austria	Albania	USSR (former)	Australia	*North Africa*	*Central America*	*East Asia*
United States	Denmark	Bulgaria		New Zealand	Algeria	Costa Rica	Cambodia
	Finland	Czechoslovakia		Papua-New	Egypt	Dominican	China
	France	Hungary		Guinea	Libya	Republic	Indonesia
	Germany	Poland			Morocco	El Salvador	Japan
	Greece	Romania			Tunisia	Guatemala	Laos
	Ireland	Yugoslavia				Haiti	Malaysia
	Italy				*South Africa*	Honduras	Mongolia
	Netherlands				South Africa	Jamaica	North Korea
	Norway					Mexico	Philippines
	Portugal				*Sub-Saharan*	Nicaragua	Singapore
	Spain				*Africa*	Panama	South Korea
	Sweden				Angola		Thailand
	Switzerland				Benin	*South America*	Vietnam
	United				Botswana	Argentina	
	Kingdom				Burkina Faso	Bolivia	*South Asia*
					Burundi	Brazil	Afghanistan
					Cameroon	Chile	Bangladesh
					Central Africa	Colombia	Bhutan
					Rep.	Ecuador	India
					Chad	Paraguay	Myanmar
					Congo	Peru	Nepal
					Côte d'Ivoire	Uruguay	Pakistan
					Ethiopia	Venezuela	Sri Lanka
					Gabon		
					Ghana		*West Asia*
					Guinea		Iran
					Kenya		Iraq
					Lesotho		Israel
					Liberia		Jordan
					Madagascar		Kuwait
					Malawi		Lebanon
					Mali		Oman
					Mauritania		Saudi Arabia
					Namibia		Syria
					Niger		Turkey
					Nigeria		United Arab
					Rwanda		Emirates
					Senegal		Yemen
					Sierra Leone		
					Somalia		
					Sudan		
					Tanzania		
					Togo		
					Uganda		
					Zaire (Congo		
					Dem. Rep.)		
					Zambia		
					Zimbabwe		