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Supply and Demand for Cereals to 2030

Pierre Crosson and Jock R. Anderson
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Resources and Global Food Prospects
Supply and Demand for Cereals to 2030

Pierre Crosson and Jock R. Anderson

The World Bank
Washington, D.C.
FOREWORD

This report was prepared in the Agriculture and Rural Development Department as a contribution to the background work for the World Development Report 1992. Most of the drafting was done by Pierre Crosson, on secondment from Resources for the Future, Washington, D.C., and the work was carried out under the direction of Jock Anderson, who also contributed the Executive Summary and significantly to Chapter 9. Useful assistance and material was variously contributed by Dennis Anderson, Charles Antholt, Shawki Barghouti, Hamdy Eisa, John English, Cees de Haan, Suzanne Gnaegy, Richard Grimshaw, Daniel Gunaratnam, Peter Hazell, Merlinda Ingco, Guy Le Moigne, Stephen Mink, Donald Mitchell, Wally Ochs, Keith Oblitas, Donald Plucknett, Herve Plusquellec, Nemat Shafik, Ashok Subramanian, Daniel Wachter, and Nick Wallis of the Bank, where Heinz Jensen provided helpful library assistance. From outside the Bank, helpful material was gratefully received from Derek Byerlee, James Longmire and Tony Fischer (CIMMYT), Prabhu Pingali (IRRI), Thomas Walker (ex ICRISAT now CIP) and Paul Dorosh (Cornell University Food and Nutrition Policy Program) and colleagues in the FAO provided many useful suggestions (unfortunately not always able to be fully taken up) on an advanced draft and for this we wish to express our gratitude to R. Brinkman, D.H. Brooks, C.G. Groom, J.P. Marathee, D. Norse, A. Papasolomontos, W.G. Sombroek, and perhaps also others unknown to us. Responsibility for the perspectives, judgments and speculations herein rests, however, with Anderson and Crosson.

Assistance with sponsorship for the work was provided within the Bank by the International Trade Division and WDR 1992 team for which we wish to thank Ronald Duncan and Andrew Steer, respectively.

The time-bound preparation period for this report obliged confining its scope and detail to less than we might have wished and rather less than the title implies, as is explained in the introductory chapter. The meeting of the WDR schedule was possible only through the tireless and efficient word processing effort of Corazon Solomon.

Michel Petit
Director
Agriculture & Rural Development Department
World Bank
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<th>Description</th>
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<tbody>
<tr>
<td>CFCs</td>
<td>Chlorofluorocarbons</td>
</tr>
<tr>
<td>CGIAR</td>
<td>Consultative Group on International Agricultural Research</td>
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<tr>
<td>CIMMYT</td>
<td>Centro Internacional de Mejoramiento de Maiz y Trigo</td>
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<tr>
<td>CPR</td>
<td>Common Property Resource</td>
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<tr>
<td>DDT</td>
<td>Dichloro-diphenyl-trichloro-ethane</td>
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<tr>
<td>EPA</td>
<td>Environmental Protection Agency (U.S.A.)</td>
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<tr>
<td>EPIC</td>
<td>Erosion Productivity Impact Calculator</td>
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<tr>
<td>FAO</td>
<td>Food and Agriculture Organization</td>
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<tr>
<td>FSR</td>
<td>Farming Systems Research</td>
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<tr>
<td>GAP</td>
<td>Gross Agricultural Product</td>
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<tr>
<td>GCM</td>
<td>Global Circulation Model</td>
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<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
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<tr>
<td>IBPGR</td>
<td>International Board for Plant Genetic Resources</td>
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<tr>
<td>ICRISAT</td>
<td>International Crops Research Institute for the Semi-Arid Tropics</td>
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<td>IFPRI</td>
<td>International Food Policy Research Institute</td>
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<tr>
<td>IIMI</td>
<td>International Irrigation Management Institute</td>
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<tr>
<td>IITA</td>
<td>International Institute of Tropical Agriculture</td>
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<tr>
<td>IPM</td>
<td>Integrated Pest Management</td>
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<tr>
<td>ISNAR</td>
<td>International Service for National Agricultural Research</td>
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<tr>
<td>LDC</td>
<td>Less-Developed Countries</td>
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<td>MDC</td>
<td>More-Developed Countries</td>
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<td>PI</td>
<td>Productivity Index</td>
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<td>RFF</td>
<td>Resources for the Future</td>
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<td>RMR</td>
<td>Resource Management Research</td>
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<td>SCS</td>
<td>Soil Conservation Service (U.S.A.)</td>
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<td>UN</td>
<td>United Nations</td>
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<td>UNDP</td>
<td>United Nations Development Program</td>
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<td>UNEP</td>
<td>United Nations Environment Programme</td>
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<td>UNESCO</td>
<td>United Nations Educational, Scientific and Cultural Organization</td>
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<tr>
<td>USDA</td>
<td>United States Department of Agriculture</td>
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<tr>
<td>WRI</td>
<td>World Resources Institute</td>
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<td>WUE</td>
<td>Water Use Efficiency</td>
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EXECUTIVE SUMMARY

This Report, prepared as a background document for WDR 92, explores
the circumstances under which the global agricultural system may be able to satisfy
the growing demands for some major foods through to 2030. It does this under the
constraint that such achievement should be at "acceptable" economic and
environmental costs.

The analysis proceeds primarily through reviewing the quantity and
quality of resources that can be mobilized -- particularly those resources relating to
land, water, plant genetic resources, climate, and knowledge about agricultural
production systems that is embedded in people, institutions and technology. In this
sense, the scope of this report is limited because there is little consideration of
macroeconomic policy, the role of changing energy prices and availabilities, and the
specific contributions of labor and conventional capital items. Whilst broad
assumptions are made about the trading environment, the specific flows of world trade
in major agricultural commodities are given little explicit attention.

The demand scenario for the next several decades is tackled primarily
by using United Nations Population Projections and some judgmental assumptions
about the changing incomes and related demands for the major cereals. It was
necessary for the projection period of the report to extend the most recent World Bank
projections to 2005 beyond to 2030. It seems that global grain consumption by 2030
will be some 97 percent greater than in the past few years and 91 percent of this
growth in consumption demand will be in LDCs. Such changing growth patterns are
not uniform across the major cereals: rice is rather stagnant whilst, driven largely by
the growing importance of animal feed, demand for coarse grains is even higher than
the growing demand for wheat.

THE LAND RESOURCE

The cropped area of the world is about 1.5 billion ha, while more than
3 billion ha is in pasture and rangeland, 4 in forest and more than 4 in urban, built-up
and other non-agricultural or non-productive uses. The disposition of the total area for
cropping in the future is of critical importance in assessing the changes required for the
implied 2.7-fold increase in food production by LDCs. To address possibilities, earlier
classifications of the potential for crop production of different categories of land are
reviewed with particular attention to crop productivity. Whilst the potential additional
cropland so classified is almost the same in total area as the presently cropped land,
much of it is of considerably lower average productivity than that presently used and
much of it could only be brought into production at high and possibly unacceptable
costs of both the economic and environmental type. It is certainly not distributed
equally across major LDC regions.

In reviewing the possibilities, several factors were considered, including
distance from market, the opportunity cost of conversion, the important soil
characteristics, and other factors that bear on land utilization, including diseases of livestock and humans, and the losses of land to urbanization. For the latter, estimates are made of the likely allocation of productive agricultural land to urban purposes over the projection period. It seems that no more than 10 percent of the land judged as having potential to be cropped could be so re-assigned over this period.

Under a combination of favorable economic circumstances encouraging conversion and the need to exploit additional lands for meeting the demand scenario, something of the order of 25 percent of the 100 percent increase in global demand for cereals might well be met through the exploitation of new agricultural lands.

Land quality is an important issue in any such long-run consideration of global agricultural production. This takes analysis into a consideration of phenomena of land degradation and desertification and the nature of the various processes at work. One important subset of this is soil erosion. Chapter 3 includes a survey of much the available evidence, which is often hardly adequate for definitive analysis. The various forms of land degradation are indeed surely a cause for great concern in specific locations but, at least from the review of studies available, it seems that, in themselves, these negative changes in inherent land productivity should not add particularly greatly to the overall supply challenge to 2030. This is not to suggest that soil erosion and other forms of degradation are not severe economic and environmental problems in some particular circumstances, and various policy measures and research issues that need to be addressed to begin to rectify such difficulties are reviewed in the discussion.

Land supply will be in especially tight supply in Asia, whilst, in principle, being more available in both Latin America and Sub-Saharan Africa. In any event, the total potential supply of additional cropland will be substantially less than the current supply of such land. Accordingly, it is necessary to explore other means of meeting the demand scenario.

THE WATER RESOURCE

Although irrigated croplands represent only about 17 percent of global cropland, they account for almost one-third of total food production, and irrigation has been an important source of growth in cereal production. In LDCs, a majority of rice and wheat is produced under irrigation. Irrigation has been the subject of major investment activities in recent decades, especially in LDCs, and it is thus pertinent to explore the opportunities for additional irrigation development.

New irrigation requires some suitability of agricultural resources and geomorphological characteristics, as well as consideration of infrastructural aspects, not to mention the supply of investment funds. Using such broad criteria, it is possible to estimate the potentially irrigable lands. The absolute and proportional increases in potential vary considerably in major LDC regions. Whilst South America and Sub-Saharan Africa have high proportional potential increases, the greatest absolute potential for increase is in the Far East. Indeed, this represents nearly 60 percent of total potential increase in LDCs. Most of the LDC potential is in just three countries - Brazil, China and India.
Whilst these are long-run potential estimates, many countries will have difficulty implementing any such major developments in the short run. China may be an exception to this but for most, the actual exploitation will be seriously restricted because of a variety of factors. For one thing, many existing systems are in parlous state, ageing and in need of rehabilitation and modernization in many countries, including such major irrigators as India. The real costs per unit area of further development are also increasing and such increases in investment costs, along with likely declining commodity-price trends, will reduce the profitability of further irrigation development.

There are pervasive difficulties of the management of existing and probably future irrigation systems. There is debate over the extent of mismanagement but most estimates indicate that large gains could be made from better management of the existing resources. Again, the achievement of these gains requires reforms of such profound significance that they are unlikely to be seen in the next couple of decades. Many authorities are, however, addressing themselves to overcoming such difficulties. For new investments there are major financial and natural resource constraints to be confronted, particularly as major investments in Sub-Saharan Africa are contemplated. In many areas of the less-developed world, there is rapidly growing competition for water from urban and industrial users and for environmental services. In yet others, widespread salinization and waterlogging problems compromise present returns on past investments and add to the difficulties of further investment in new schemes.

All in all, the prospect for increasing global supplies of irrigation water to contribute in a major way to the needed increases in supply of basic foodgrains seems an unlikely one. However, its contribution to increased production in selected countries is likely to be sizeable.

**THE PLANT GENETIC RESOURCE**

The Green Revolution dating from the mid-1960s has underscored the importance of plant breeding in improvement of crop productivity and this, in turn, highlights the importance of access by plant breeders to a wide range of crop genetic resources.

Plant genetic resources for this directly productive purpose are maintained in various collections throughout the world. Some of the most important collections of relevance to food production are managed under the aegis of the CGIAR Centers and one of the Centers (IPGRI) is especially involved in fostering the collection, conservation, evaluation, maintenance of access to such resources.

The situation varies somewhat amongst crops. Some crops are notoriously difficult to handle in this sense, particularly those that must be propagated primarily through vegetative means, such as much of the potato collections, for instance. Indeed, the major foodcrops are probably in better shape in this respect than are some of the industrial crops, such as rubber and cocoa.
There are many problems in exploiting such collected materials. One is to successfully manage the genebanks as viable reproducible stocks of seeds or other plant materials. Another is the distribution of the resource to those who would use it throughout the world and this involves confronting national plant quarantine policies and procedures. In some cases, particularly in handling possible viral transmissions, it is extremely difficult to be absolutely safe and thus the sharing of plant genetic resources can actually compromise the disease status of a country.

It seems reasonable to generalize, however, that the state of plant genetic resource conservation is such as to see this as not a serious constraint to the development of the needed more productive food-crop cultivars, although it would be reassuring to know that collectors are more actively exploring for wild relatives than they may have been in the past. There are other pressing reasons to collect and conserve genetic resources, and some of these are broached below in paragraph xxvii in the discussion below of biodiversity.

**THE CLIMATE RESOURCE**

There has been little noticeable change in world climate in recent decades and the question for this report is whether this situation will continue to prevail for the next few decades.

There has been much concern expressed in recent times about the enhanced Greenhouse Effect and the associated inevitable global warming, as well as the effects of such warming on the climates of the world. These studies use global circulation models to link the changed composition of the atmosphere under various scenarios to the particularities of climate in given regions. The studies are frustrating in their inability to be precise as to even general effects such as average temperature change and are much less certain for important agricultural variables such as precipitation in particular seasons and the variability of such precipitation.

It is thus very much an art form to ascribe likely changes in agricultural production to such changed climatic scenarios. The uncertainties are overwhelming and there is little precise knowledge to be reported upon. It seems reasonable, however, to conclude that, at least for the next four decades or so, the changes will not be great. Even a conclusion of this nature probably overstates the likely consequences, since the models that have been used do not allow for the adjustment behavior that human operators such as farmers would naturally make as new realities are comprehended. Accordingly, for the purposes of this projection exercise, it is assumed that climate will continue in its highly variable way to drive global food production in more or less the same way that it has in the recent past and, at least in this sense, will not likely prove to be an additional constraint on agricultural progress - but neither will it likely provide much scope for meeting the needed increases in production.
ECONOMIC AND ENVIRONMENTAL COSTS

The growing concern for the state of the global environment means that environmental costs are taking on increasing importance in discussion of the state of the present agricultural world and its likely evolution over the next several decades. Agricultural practices are coming under greater scrutiny for their environmental consequences. Many practices generate externalities, usually negative ones for those users affected either downstream or in neighboring micro-environments. The consequences of some such externalities for global warming have already been broached but, in this section, the attention is concentrated on those economic and environmental costs that pertain particularly to the land and water resources, as well as to genetic diversity generally.

Many of the environmental costs incurred in production are unpriced and are often most importantly incurred off farm. That is, farmers may generate them but are not directly responsible to others for the damage that they may cause. The preceding discussion of the likely feasible increases in cultivated area recognized that it is not just the economic costs incurred in new land cultivation but, rather more importantly, the environmental costs that will be most significant in constraining further exploitation.

The text discussion of environmental costs is focused on the importance of property rights in influencing behavior. Where property rights for whatever reason cannot be attributed to a resource, the environmental costs tend to be high and not readily amenable to intervention.

One important source of environmental concern relates to the use of agricultural chemicals. Pesticide use has grown considerably in recent decades, and doubtless has been of significance in fostering growth, but it is also a demonstrable source of severe damage in particular circumstances. People can be damaged themselves but of greater global significance is the development of resistance amongst the target organisms. These, in turn, cause consequent productivity loss and an unfortunate tendency to increase rates of pesticide use and thus to exacerbate the problem. The good news in this area is that the combination of modern highly toxic short-duration pesticides and managerial schemes for minimizing use of pesticides, such as the very information-demanding integrated pest management schemes, seems likely to develop at a sufficient rate to bring this environmental problem under control and at acceptable or at least more-acceptable environmental costs.

To take another key concern, the sediment arising from eroded lands can cause many forms of damage for downstream users. Siltation of reservoirs with consequent reduction in their economic life for both electricity generation and provision of irrigation water is one dramatic form of loss. In other cases, it has to be recognized that the incoming sediment can benefit downstream users who gain fresh influxes of possibly high fertility soil -- although this is not always such a happy story. Whatever may be the particular situation, there is clearly an externality and one where novel forms of intervention are required to encourage upstream users to control their sediment loss and thus the environmental costs that they impose on others.
The final brief example considered here is that of biological diversity, whereby there is existence value in maintaining the store of biological wealth for purposes yet unknown to humankind. Agriculture, especially to the extent that it makes inroads on the biologically rich rainforest areas, for instance, must accept some responsibility for this form of environmental cost, namely, the loss in value of biodiversity. Policies are thus required urgently to contain forest-clearing proclivities and to endeavor to bound the future tendencies for loss of biological diversity.

Just how the growth of agriculture in the areas sketched here will impact on environmental costs in the large can only be speculated about but seems surely to be a growing difficulty. Property rights are certainly important in individual decisions concerning resource management. At least to the extent that some of the user costs are internalized into the decision making of farm operators, better decisions will be made about managing the resources in an enduring way.

Where private rights are well entrenched, soil erosion is typically not such a problem and is certainly amenable to intervention through policies that encourage better custody of the resource. Where common property resources are involved, resource management can still work fairly well providing that the common rights are well respected. The real difficulty lies in open-access resources, where the difficulties such as the "tragedy of the commons" are notorious. Here the development imperative is to restrict access by some form of property rights legislation or regulation - something that is often easier said than done, particularly under the pressure of high population growth rates.

THE KNOWLEDGE RESOURCE

Improved knowledge can substitute in many ways for other resources in production. One of the best things about the knowledge resource is that it is responsive to investments in the knowledge industries and in this way it is much more elastic in its supply than the resources that have been discussed above.

It has long been recognized that investments in knowledge will assist through their productivity-enhancing consequences to boost agricultural output. The question at the moment is whether the same form of growth will persist in the needed manner over the next several decades. Thus the question being asked here, given the constraints to farming new agricultural lands, the difficulties with the supply of new irrigation waters, and the other generally constraining resource situations, is: Can knowledge in itself indirectly provide the needed growth? This is a complex question that cannot be simply answered in a usefully informative way and is tackled here in a crop-specific review of opportunities.

Whatever may be the eventual realized yields that come through changing agricultural technology, it is important to recognize that much of such gain will derive from formal investments in research and development activities, including extension activity whether handled publicly or privately. The key consideration is that much research will continue to provide products that are nearly pure public goods and thus it is to be understood in the subsequent discussion that public investment in agricultural research, both nationally and internationally, will need to be sustained at
high levels to give the needed sources of technological advance and ultimately growth in production. There are some important exceptions to this public-good rationale for agricultural research but these are likely to have small to moderate changed productivity influence over the projection period. Such exceptions involve the private sector and those innovations that are appropriable.

Rice productivity continues to grow in farmers' fields, in some regions in part through greater use of hybrids and also increasing cropping intensity, although there have been recent worrying concerns that potential yields on experiment stations have changed remarkably little and, in some cases, may even be diminishing. The application of modern molecular biology will surely eventually lead to profound effects in rice productivity but this will certainly not happen too quickly and will probably not be a very major contributor to yield growth as such over most of the projection period. Some exciting things probably will happen, particularly in the field of improved disease resistance, and associated reduction in use of agricultural chemicals, and just possibly a significant increase in crop-yield potential. Other more ambitious innovations such as the ability of rice and other cereals to fix nitrogen are much more futuristic. The guess here is that, given sustained provision of research resources, rice research workers can provide the means for the modest gains required in yields to meet the growing demands of the world, largely in Asia, for rice.

The production and research situation for wheat and coarse grains are rather different. Biotechnology will also eventually play its role here too but the production environments for much of the world's wheat and even more of the world's coarse grains are usually rather more difficult and variable, and are more challenging as a research enterprise. Notwithstanding such features of many wheat-growing areas, and the differences of opinion held by various wheat researchers, it is judged that just under 2 percent a year yield growth is achievable, including gains from both improved crop management and improved varietal performance. This would leave relatively modest area effects to take up the slack to meet the demand scenario.

Things do not look quite so readily achievable for coarse grains, however. The most important one of these is and will be maize, and the difficulty that crop-improvement specialists face is that maize is grown under exceedingly diverse agroecological conditions, especially in LDCs. The potential for yield enhancement is well documented through the achievements in the more-favored regions of MDCs and thus it is primarily a matter of bringing the research resources to bear in the diverse ecologies that have thus far, relatively speaking, been neglected. This can probably be done readily enough for maize but there is rather greater difficulty in making comparable achievements with the other two major coarse grains, namely, sorghum and millet, which tend to be grown in much drier and more difficult areas. For all these crops, hybridization work and good crop management can produce high yields, but not in the more difficult areas of the less-developed world where they are relatively more important.

Overviewing the technological options and possibilities for all these major cereals and, to re-emphasize the point, assuming a sustained investment in appropriate research and development work, including especially improved natural-resource management, the demand scenario seems to be achievable. With a little help from the MDCs and the more successful exporting LDCs, the overall supply situation seems to be reasonably well-matched to the demand scenario.
The mentioned resource-management work, slow and frustrating though it may be, will be increasingly important in underpinning any such technological gains and in simultaneously addressing the environmental costs that will otherwise be incurred at unacceptably high levels. Such work is something of an infant, or even orphan, "industry" in many situations, and thus it can be expected that there will eventually be good rates of social return to new programs of natural resource-management-oriented agricultural research in LDCs, particularly if it focused on low-cost but effective innovations that can be readily and profitably implemented by the billions of farming resource managers who, given appropriate private incentives and command of an adequate base of resources, surely stand ready to respond to society's needs for food supply and agricultural resource custody.
CHAPTER 1
OBJECTIVE AND STRUCTURE OF THE REPORT

Objective

This report is addressed to the broad question: can the global agricultural system satisfy rising demand for food and fiber out to the year 2030 at "acceptable" economic and environmental costs? Costs are understood to include those borne by people living between now and 2030, as well as costs imposed on subsequent generations by management of the system between the 1990s and 2030. The paper thus is about the sustainability of the global agricultural system in the sense that one's judgment of whether the system is or is not sustainable likely would depend on whether the answer to one's question is yes or no.

The emphasis on economic and environmental costs in the question addressed indicates that the paper is focused primarily on the supply side of the global agricultural system. However, the economic and environmental costs of increasing supply depend importantly on the rate of increase in global demand for food and fiber. Other things the same, holding economic and environmental costs within "acceptable" limits confronts more problems at higher rates of demand growth than at lower rates. More specifically, the pressure of agriculture on the natural resource base and environment, and the importance of finding ways to ease the pressure, are greater with higher than with lower rates of global demand growth.

Consequently the capacity of the agricultural system to respond satisfactorily to rising demand -- the sustainability of the system -- cannot be assessed without some notion of the likely growth in global demand for food and fiber.

The supply response to increasing demand, and the consequent behavior of economic and environmental costs, will depend on the quantity and quality of the resources that, on a global scale, can be mobilized for agricultural production. We concentrate here on five categories of resources: land, water, plant genetic resources for crop breeding, climate resources, and knowledge about agricultural production embedded in people, institutions and technology. At any given time, these resources may be combined in relationships of both complementarity and substitutability, depending on technical and economic conditions. Over the past 50 years, however, knowledge has increasingly substituted for the other resources, as it has proved far easier to increase the quantity and quality of knowledge than the quantity and quality of other resources.

All present evidence, including that marshalled in this report, indicates that this trend in the relationship between knowledge and the other resources will continue into the indefinite future. Indeed, the critical question in the issue of agricultural sustainability is what, over the long-term, are the limits, if any, of substitution of
knowledge for the other resources employed in agricultural production? This view of
the sustainability issue determines the structure of this report.

Structure of the Report

As noted, the sustainability issue cannot be productively addressed without
some scenario of the future growth of global demand for food and fiber. Chapter 2
sketches such a scenario for 2005 and 2030 to set the scale of the challenge to the
agricultural production system. Chapters 3 to 6 consider prospects for increasing
supplies of land, water, genetic resources and climate resources, respectively, in
response to the demand scenario. The assessment assumes no change in the current
supply of knowledge about management of the resources in agricultural production.

Chapter 7 considers the likely impact on environmental and economic costs if
the supply of knowledge were held constant and the only way of responding to the
demand scenario were to increase the supplies of land, water, plant genetic resources
and climate resources. Although no quantitative estimates are made, the conclusion
is that, under the assumed supply conditions, environmental and economic costs
would rise to unacceptably high levels.

Chapter 8 then considers the potential for increasing the productivity of land
and water resources by drawing on presently known, but not widely used,
technologies and practices for managing the resources. The conclusion is that there
are some potential productivity gains in this area but that they would be insufficient
to prevent unacceptable increases in environmental and economic costs. Avoidance
of this outcome will require major increases in the supply of new knowledge. The
prospects for achieving this are discussed in Chapter 9. Chapter 10 presents a
synthesis of the main arguments and conclusions of the report.

Limited Scope of the Report

The issue of how to achieve sustainability of the global agricultural system
poses problems on an enormous scale, and a full treatment of the issue is well beyond
the scope of this report. We have not dealt, for example, with the role of the
international economic environment or with national macroeconomic policies which can
be important in shaping farmers' resource management decisions. Changes in these
factors could either facilitate or make more difficult the attainment of global agricultural
sustainability, but treatment of them is not included in our brief.

Although the supply of energy is critically important to agricultural
sustainability, we do not consider it because it is not specific to agriculture. Energy
analysts at Resources for the Future expect real energy prices to rise over the next
several decades although at a slower annual rate than in the 1970s and early 1980s.
Increasing energy prices would make achievement of agricultural sustainability more
difficult than if prices did not rise; but higher energy prices are not per se inconsistent
with sustainability. World agricultural production continued to increase and crop prices
to fall throughout the second half of the 1970s and all of the 1980s. Farmers generally found ways to use energy more efficiently as its price rose.

The low-income countries have been shifting for some time from wood and other biomass sources of energy to commercial fossil fuel sources. The shift has been driven in large part by the combination of rising labor costs in those countries and the increasing scarcity of wood. The labor time required to collect a unit of wood has increased simultaneously with a rise in the cost of labor time. The increasing substitution of commercial energy for wood suggests that the costs of wood have increased faster than commercial energy prices, despite the increase in the latter over the past couple of decades. These trends are expected to continue for several decades, in which case the expected rise in commercial energy prices might have a smaller negative impact on use of energy poor countries, especially in rural areas, than in the more developed countries where the transition from wood to fossil fuels was completed decades ago.

The demand scenario developed in the next chapter includes rising per capita income in both more- and less-developed countries, implying rising labor income, including income of agricultural labor. This increase in the cost of labor, however, would not be a threat to agricultural sustainability but rather a condition of it. That is, any agricultural system that, over the long term, failed to generate rising income for farm workers likely would be judged unsustainable by the society of which the system was a part.

Supplies of fertilizer, pesticides and farm machinery and equipment are assumed not to constrain the expansion of global production in response to the demand scenario. This is not because we believe supplies of these resources can, in fact, be taken for granted but because analysis of them is outside the bounds of this report.

The Role of Trade

The issue of sustainability cannot be sensibly addressed without making explicit assumptions about trade among production units, be they individual farms, localities, regions or nations. For any such unit, trade opens up opportunities for avoiding "unacceptably high" production costs by substituting imports for the unit's own production when that level of costs is approached. In general, the more robust and extensive the trading system, the greater the probability that all production units will achieve sustainability.

In this report, we assume that the robustness of the agricultural trading system linking localities, regions and nations will remain as it is presently. An implication of this is that, as these production units observe that their responses to increasing demand will impose unacceptably high costs on them, they will view the trading system as a way out and, at the margin, will be willing to substitute imports for their own production. Of course, judgments of what constitutes unacceptably high costs will vary among units. Some nations, for example, may be willing to accept higher costs than others because they put a higher value on greater food self-sufficiency.
Nevertheless, we assume that the trading system will continue to provide important opportunities for nations to escape rising production costs and that all of them, in varying degrees, will be willing to take advantage of the opportunities. This bold assumption embraces also the nation states that once constituted the Soviet Union. The present uncertainties are such that we have dodged the difficulties of assessing the short-term cereal import demands of the CIS, and the even greater challenge of documenting the timing of when it will become the major cereal exporter that it will surely eventually be.
CHAPTER 2
THE DEMAND SCENARIO

Introduction

To assess the sustainability of the global agricultural system, we need some notion of the demand pressure that might be brought on the system. We need a demand scenario. Given the supply side focus of this report, however, the scenario need not be written in great detail. It will suffice to make a plausible case that, over the period to 2030, global demand for aggregate agricultural output will increase by some factor X.

The scenario sketched here deals primarily with future global demand for grains. Grains are estimated to account presently for roughly one-half of global consumption of food energy; and, as animal feed, grains also account for a rising share of global protein consumption. Soybean is an important high-protein food for people and, especially, for animals. Soybean production, however, is highly concentrated in four countries: the United States, Brazil, Argentina and China, making it, for the supply-side perspective taken here, a special case, left for treatment at another time. We thus do not include soybeans (or other oilseed crops) in the demand scenario.

This is a report largely about cereals but, lest we be accused of a "cereal mentality," we make brief mention of non-cereal staples both here and in Chapter 9. Root crops and tubers presently are significant in the diet of many people in the less-developed world, particularly in Africa, parts of rural Latin America, the Caribbean and the Pacific Islands. Data suggest that per capita consumption in those regions has been declining in the past two decades (see Table 2.1) but these data should be viewed with some skepticism, due to the poor overall quality of root-crops data. It is not clear from the scant statistics that are available, however, whether this is a reflection of changing consumer preferences, or rather availability. Declining consumption is sure to be a function of the rate of urbanization and the resulting relative scarcity of the highly perishable staples, as well as the relative availability and cheaper prices of imported cereals in major urban areas. Positive, albeit small, income elasticities indicate they are not inferior goods, as is generally believed.

Roots and tubers provide about one-third of the energy of a weight-equivalent quantity of grains, but they ensure an energy output per hectare per day considerably higher due to high-volume yields. Their importance comes not from the absolute volume of either production or consumption, but from the fact that, in areas where consumption of roots and tubers is greatest, their proportion of total daily energy intake can reach as high as nearly 60 percent in parts of Central and non-Sahelian West Africa (the average for Sub-Saharan Africa is about 20 percent). It is also useful to remember that, in general, the populations that consume a significant proportion of dietary food energy from roots and tubers do so at a much higher rate in times of
Table 2.1: Projections of Demand for Cassava to the Year 2000

<table>
<thead>
<tr>
<th>Region</th>
<th>Total annual demand (Mt)</th>
<th>Demand per capita (kg/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asia</td>
<td>27.2</td>
<td>4</td>
</tr>
<tr>
<td>Sub-Saharan Africa</td>
<td>70.7</td>
<td>11</td>
</tr>
<tr>
<td>Latin America</td>
<td>16.8</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>114.7</td>
<td>18</td>
</tr>
</tbody>
</table>


Drought or food shortage caused by market failures or other factors external to the agricultural sector (such as war).

The demand for animal products is assumed to be reflected primarily in the demand for feedgrains. However, the resource and environmental impacts of forest clearing to grow crops or graze animals are considered in the supply-side assessment. Crops grown primarily to produce drugs, legal or illegal, are not included in the demand scenario. There is no reason to believe that, in the aggregate, demand for the several excluded crops will not grow at more or less the same rate as will demand for grains. In any event, divergence of growth rates of some crops from those for grains would make little difference for the purposes of this scenario.

If the main focus of this report were on prospective increases in demand for all agricultural commodities, this way of treating demand would not suffice. However, the focus here is on conditions for increasing global agricultural production at acceptable economic and environmental costs. For this purpose, we need a demand scenario that defines in broad terms the challenge to increasing global supply. The challenge need not be defined in detail by crop.

The Scenario to 2005

The terminal date (determined by others) of the demand scenario for this report is 2030. However, the International Economics Department (1990) of the World Bank prepared a scenario of demand for grain in the less-developed countries (LDCs) in 2005, which provides a useful guidepost along the route to 2030. So we first consider this scenario and later we extend it to 2030, and include demand in the more-developed as well as in the LDCs.
Table 2.2 shows data and projections of grain consumption in LDCs from the International Economics Department's report, as well as world totals. The report gives little detail on how the projections were made, but notes that they reflect overall economic growth, macroeconomic conditions, and some policy changes in the major producing regions, particularly in the Peoples Republic of China, in the Soviet Union, and in more-developed countries (MDCs) with respect to management of agricultural surpluses. The projections assume continuation of price and income support programs in the MDCs. In another place (Mitchell 1991), the important role of population growth in stimulating demand for food in the Asia/Pacific region is noted. The point holds for Africa and Latin America as well.

The International Economics Department’s report (1990) also emphasizes the demand-stimulating roles of rising per capita income and urbanization in poor countries, not only in providing the wherewithal to spend more on food but also in shifting preferences among kinds of food. Table 2.2 indicates that, in the LDCs, wheat consumption grew 3.7 percent annually from 1979/81 to 1988/89, compared to 2.1 percent annually for rice and coarse grains combined. Some 84 percent of the growth in wheat consumption was in Asia, where the annual rate of growth was 4 percent from 1979/81 to 1988/89.

Experience in Korea illustrates the effects of rising per capita income and urbanization in shifting consumer preferences toward wheat. Ingo (1990) shows that, between 1965 and 1978, a period of extremely high per capita income growth and rapid urbanization in Korea, the income elasticity of demand for rice fell from 0.26 to 0.03. The income elasticity of demand for wheat also fell, but not nearly so much, and demand for coarse grains increased sharply, reflecting increased preference for animal products.

Table 2.2 also demonstrates the dominance of Asia in grain consumption in LDCs. In each of the three periods shown, Asia accounts for about 75 percent of total grain consumption in these countries. Asia's share of rice consumption was 93 percent in each period, and its share of wheat and coarse grain consumption combined was almost two-thirds. The dominance of Asia in wheat and coarse grain consumption in LDCs reflects the region's relatively large population, since its per capita income on average is less than in Latin America and not much greater than in Africa. Asia's dominance in rice reflects both its large population and the fact that rice by long historical tradition is peculiarly an Asian crop.

The dominance of Asia, especially in rice, gives point to the earlier cited study by Mitchell (1991) of grain consumption in the Asia/Pacific region. Mitchell notes that the region's share of world grain consumption rose from one-third in 1964-71 to 40 percent in 1988. In the latter year the region accounted for 90 percent of global rice consumption, and for 37 percent, 24 percent and 25 percent of global consumption of wheat, coarse grains and soy oil and meal, respectively. Mitchell also shows that per capita rice consumption in the region rose from about 90 kg in the early 1960s to 110 kg in 1985, then declined slightly in following years. Per capita wheat consumption increased more or less steadily from 32 kg in 1960 to 68 kg in 1988. Per capita consumption of coarse grains was marked by a changing pattern of consumption, directly as food and indirectly as feed for animals. Direct coarse grain
Table 2.2: Grain Consumption in Less-developed Countries (Mt/y)*

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wheat</td>
<td>Rice*</td>
<td>Coarse grains</td>
<td>Total</td>
<td>Wheat</td>
<td>Rice*</td>
<td>Coarse grains</td>
<td>Total</td>
</tr>
<tr>
<td>Asia</td>
<td>149.8</td>
<td>231.2</td>
<td>147.7</td>
<td>528.7</td>
<td>208.3</td>
<td>288.1</td>
<td>171.2</td>
<td>667.6</td>
</tr>
<tr>
<td>PRCb</td>
<td>75.1</td>
<td>97.9</td>
<td>84.3</td>
<td>257.3</td>
<td>103.3</td>
<td>124.4</td>
<td>90.9</td>
<td>318.6</td>
</tr>
<tr>
<td>Other</td>
<td>74.7</td>
<td>133.3</td>
<td>63.4</td>
<td>271.4</td>
<td>105.0</td>
<td>163.7</td>
<td>80.3</td>
<td>349.0</td>
</tr>
<tr>
<td>Africa</td>
<td>23.6</td>
<td>7.6</td>
<td>53.8</td>
<td>85.0</td>
<td>30.5</td>
<td>8.7</td>
<td>63.2</td>
<td>102.4</td>
</tr>
<tr>
<td>Latin America</td>
<td>22.2</td>
<td>10.6</td>
<td>59.3</td>
<td>92.1</td>
<td>26.8</td>
<td>12.4</td>
<td>65.3</td>
<td>104.5</td>
</tr>
<tr>
<td>Total</td>
<td>195.6</td>
<td>249.4</td>
<td>260.8</td>
<td>705.8</td>
<td>265.6</td>
<td>309.2</td>
<td>299.7</td>
<td>874.5</td>
</tr>
<tr>
<td>World total</td>
<td>446.2</td>
<td>273.2</td>
<td>744.0</td>
<td>1463.4</td>
<td>534.0</td>
<td>325.8</td>
<td>808.4</td>
<td>1668.2</td>
</tr>
</tbody>
</table>

Source: LDCs from International Economics Department (1990); world totals from U.S. Department of Agriculture (1990).

* The units and abbreviations used in this report are the official metric conventions of the System Internationale wherein t denotes tonne (= 1000 kg), y year and the prefix M denotes mega (= million).

b Peoples Republic of China.

* Rice data are in hulled rice terms.
consumption per capita was steady at about 41 kg from 1960 to the late 1970s, then declined to an average of about 30 kg in the late 1980s. Over the same period, per capita consumption of coarse grains as animal feed increased from about 7 kg in 1960 to an average of 16 kg in the late 1960s to late 1970s, then rose steeply to about 37 kg in 1988. These increases and changing patterns of grain consumption in the Asia-Pacific region are broadly consistent with the experience of Korea, as indicated in Ingco (1990).

Table 2.3 shows average annual rates of increase in LDC consumption of the three crops from 1979-81 to 1988-89 and from the latter years to 2005. The projected aggregate rate is about the same as the historical rate -- 2.5 percent and 2.6 percent, respectively. The projected rates for wheat and rice, especially wheat, are less than the historical rate, however, and the projected rate for coarse grains is higher. These differences reflect the assumption that the changes in consumption patterns observed in Korea and elsewhere in Asia from the mid-1960s to the late 1980s will occur in the LDCs generally over the next decade and a half, although probably not to the same extent as in Korea.

The Scenario to 2030

Crosson and Katz (1991) developed projections of global grain consumption for 2030. Those projections have been adapted to make them consistent with the projections of the International Economics Department for 1988-89 to 2005. Crosson and Katz made two projections, one for the LDCs and one for the MDCs, including what was the Soviet Union and Eastern Europe among the latter. They assumed that, over the period to 2030, demand for grain in the MDCs, as registered at the farm gate, would increase only with population. In most of these countries per capita income is high enough that most people now consume grain, again as registered at the farmgate, at close to the biologic limit. Consequently, increases in per capita income add little if anything to farm-gate demand for grain. Indeed, per capita grain consumption in the United States, Canada and Western Europe evidently declined in the 1980s, judging from estimates by Sanderson (1988) for 1980-81 and grain consumption and population data for those countries at the end of the 1980s. One possible explanation for this is that consumer preferences have shifted, seemingly for health reasons, from beef to poultry and fish, which would tend to decrease grain consumption.

Income in most LDCs is such that many people are ill-nourished, making demand for food responsive to increases in per capita income. This situation is likely to persist over the period to 2030, indicating that, in these LDCs, demand for grain will increase with both population and per capita income.

Crosson and Katz assumed that per capita income in the LDCs would increase 2.7 percent annually from the late 1980s to 2030, the same as the rate from the mid-1960s to the late 1980s. They also assumed that per capita grain consumption in these countries would continue to grow at the same rate as from the mid-1960s to the late 1980s, namely 1.2 percent annually. They considered that these two
Table 2.3: Consumption Growth Rates in Less-Developed Countries  
(average annual percent)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>3.7</td>
<td>3.0</td>
</tr>
<tr>
<td>Rice</td>
<td>2.6</td>
<td>2.4</td>
</tr>
<tr>
<td>Coarse grains</td>
<td>1.7</td>
<td>2.2</td>
</tr>
<tr>
<td>Total</td>
<td>2.6</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Source: Derived from Table 2.2.

assumptions would more likely over-estimate than under-estimate the growth of LDC grain consumption. The 2.7 percent annual increase in per capita income is high by comparison with other projections (Nordhaus and Yohe 1983; Sanderson 1988). If per capita income were to grow that rapidly, it would triple from the late 1980s to 2030, reaching a high enough level in many countries to bring the proportion of additional income spent on grain below the level assumed by Crosson and Katz.

The Crosson and Katz projection for per capita grain consumption in the LDCs in 2030 was 393 kg. When this is multiplied by the United Nations (1989) medium population projection for that year, total grain consumption in those countries comes to 2950 Mt.\(^1\) This figure appears inconsistently high when judged by the growth trajectory in the International Economics Department projections for 1988-89 to 2005. Table 2.3 indicates that the Department's projection for all grains as an aggregate implies an average annual increase in consumption over that period of 2.5 percent. Total consumption in 2005 would then be 1319 Mt. If consumption increased from that year to 2950 Mt by 2030, the average annual rate of increase would be 3.3 percent. There is no reason why the consumption growth rate should be the same from 2005 to 2030 as from 1988-89 to 2005. But if the rate is to be different after 2005, the reasons for it to be less seem at least as strong as those for it to be more. The United Nations population projections for the LDCs show slower growth from 2005 to 2030 than from 1990 to 2005. Rising per capita income in those countries would accelerate demand for coarse grains as animal feed, but the higher income could

\(^1\)The UN projections are for every fifth year from 1990 to 2025. We extrapolated the projection for 2025 to 2030 on the assumption that growth from 2025 to 2030 would be at the same arithmetic rate as from 2020 to 2025. Henceforth, (for convenience of expression) we refer to the 2030 projection as "the UN projection".
also slow the growth of demand for rice and wheat, especially rice, as the experience of Korea suggests.

We conclude that, if LDC grain consumption grows from 1988-89 to 2005 in accordance with the International Economics Department projections (Table 2.2), it is unlikely that growth from 2005 to 2030 would be as rapid as the Crosson and Katz projections imply. The question then becomes: What would a plausible lower projection for 2030 look like? There are many possibilities. We decided to take per capita grain consumption in present-day Japan as a guide as to how much the presently poor countries as a whole might consume on a per capita basis in 2030. Although Japan is a high-income country, its per capita grain consumption (350 kg in the late 1980s) is much lower than in other high-income regions (e.g., 440 kg in the European Community and 840 kg in the United States).

Because per capita income in the LDCs as a group will still be less in 2030 than in present-day Japan, even after four decades of annual growth at a robust rate of, say, 2.5 percent, we assume that per capita grain consumption in those countries in 2030 will be 315 kg, 90 percent of the current rate in Japan. Multiplying this number by the projected LDC population for 2030 gives a projection of total LDC grain consumption in 2030 of 2350 Mt, some 20 percent less than projected by Crosson and Katz (1991). We disaggregated this number among rice, wheat and coarse grains in the following manner. Drawing on the experience in Korea and elsewhere in Asia, as reported in Mitchell (1991), we assumed that, over the period 2005-2030 the income elasticity of demand for rice would be zero, which is to say that rice consumption in these countries (over 90 percent of it in Asia) would grow only with population, some 1.3 percent per year, according to the United Nations (1989) projections. We assumed that wheat consumption from 2005 to 2030 would grow at the same rate as total grain consumption, 2.3 percent according to our projection. The wheat projection thus allows for considerable further increases in per capita consumption beyond 2005. The 2030 projection for coarse grains then was found as the residual difference between the total projection of 2350 Mt and the sum of the rice and wheat projections.

The results of these various calculations for the LDCs are shown in Table 2.4 along with a projection for the MDCs. The main question to ask about the projections in Table 2.4 is whether they are plausible given current trends and evidence about how the trends might change under conditions of rising per capita income. We believe the projections meet that plausibility standard. Clearly, however, different results would be obtained with equally plausible assumptions about population and per capita income growth and about changing demand elasticities for grains, e.g., those in Crosson and Katz (1991). The projections in Table 2.4, therefore, should be taken as no more than one set from a number of equally plausible demand scenarios. For comparison, Crosson and Katz (1991) projected global grain consumption in 2030 to be 3804 Mt, 15 percent more than the projection of 3297 Mt shown in Table 2.4. Given the many uncertainties attaching to both projections, as in all such exercises, the 15 percent difference over 40 years is small.

Table 2.4 indicates that from 1988-89 to 2030 global grain consumption would increase 1620 Mt (97 percent), 91 percent of which would be in the LDCs. According
Table 2.4: Grain Consumption in the Less-Developed and More-Developed Countries (Mt and average annual percent changes from previous period)

<table>
<thead>
<tr>
<th></th>
<th>1979-81</th>
<th>1988-89</th>
<th>2005</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vol.</td>
<td>Vol.</td>
<td>%</td>
<td>Vol.</td>
</tr>
<tr>
<td>Wheat</td>
<td>195.6</td>
<td>265.6</td>
<td>3.7</td>
<td>432</td>
</tr>
<tr>
<td>Rice</td>
<td>249.4</td>
<td>309.2</td>
<td>2.6</td>
<td>459</td>
</tr>
<tr>
<td>Coarse Grains</td>
<td>260.8</td>
<td>299.7</td>
<td>1.7</td>
<td>428</td>
</tr>
<tr>
<td>Total</td>
<td>705.8</td>
<td>874.5</td>
<td>2.6</td>
<td>1319</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>1988-89</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vol.</td>
<td>%</td>
</tr>
<tr>
<td>All Grains</td>
<td>802.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Source: LDCs, all years except 2030 from International Economics Department (1990); 2030 as described in the text. More-developed countries for 1988-89 is the difference between LDCs and global grain consumption from US Department of Agriculture (1990). Projection to 2030 assumes total consumption grows with population as projected by the United Nations (1989).
to estimates of the U.S. Department of Agriculture, grain production in the LDCs grew at an average annual rate of slightly more than 3 percent from the mid-1960s to the late 1980s, considerably more than the 2.3 percent rate of increase in consumption projected to 2030. The rate of production increase slowed in the 1980s, however, for reasons that are not immediately transparent to us. In any case, the fact that the projected percentage rate of consumption increase is less than the rate of production increase over the past couple of decades is no ground for complacency about the capacity of the LDCs to meet prospective food demands at acceptable economic and environmental costs.

Conclusion

In the following chapters, the demand scenario sketched in Table 2.4 is taken as the challenge confronting the global agricultural system over the next 40 years. Can the system increase the supply of food in response to the demand scenario at economic and environmental costs consistent with the aspirations of people all around the world, especially in the LDCs, for a rising standard of welfare? That is the broad question addressed in the rest of the paper. Because almost all of the projected increase in grain consumption is in the LDCs, the focus is mainly on them.

The relatively low growth in grain consumption projected for the MDCs, taken with their capacity to increase production demonstrated over the past 40 years, suggests that these countries could continue to be important suppliers of grain to the rest of the world, thus taking some of the pressure off the natural resource and environmental base of the LDCs. For this to happen, the MDCs would have to maintain a strong capacity to produce grain, the international trading system would have to be robust, and many countries would have to be willing to accept grain imports on a large scale. Although some or all of these conditions may not hold, analysis of them is beyond the scope of this report. Accordingly, the discussion that follows assumes that the conditions will be met.
CHAPTER 3

THE LAND RESOURCE

Introduction

This chapter considers the present and potential global supply of land for agricultural production. Both quantitative and qualitative conditions of supply are considered. The major emphasis is on supply for crop production, but attention is given also to range land. The focus is mainly on the LDCs.

The Quantity of Land

Estimates of Potential Cropland

The Food and Agriculture Organization (FAO) (1988) estimates that approximately 1.5 billion hectares (ha) were in crops in the mid-1980s, 3.25 billion ha were in pasture and range, 4.0 billion ha were in forests and 4.25 billion ha were in urban and built-up uses, wasteland, or otherwise not available for agriculture or forestry.

Estimates by the US Department of Agriculture (USDA) indicate that in 1986/1990, approximately half the world's cropland was in rice, wheat, coarse grains\(^1\) and soybeans (Table 3.1). Other important crops are sugar cane; oil seeds, other than soybeans; various kinds of hay crops; root crops, such as cassava; cotton; and tree crops such as coffee, tea, and rubber.

The roughly twofold increase in global demand for food by 2030 projected in Chapter 2 (2.7-fold for the LDCs) would increase pressure to bring more land into crop, and possibly animal, production. Estimates of land use in 1975 and of land with potential at that time for crop production are shown in Table 3.2. The numbers in the table were compiled by Buringh (1982) in connection with a conference organized by the FAO, the United Nations Environment Programme (UNEP) and the United Nations Educational, Scientific and Cultural Organization (UNESCO). Note that the 1.5 billion ha of cropland for 1975 is the same number used by the FAO (1988) for the mid-1980s (see footnote a, Table 3.1), indicating that 1.5 billion ha is a rough approximation of the amount of land in crops worldwide in the 1970s and 1980s.

\(^{1}\)Coarse grains consist primarily of maize, sorghum, barley, oats, and millet.
Table 3.1: World Land in Rice, Wheat, Coarse Grains, and Soybeans, in 1986/90

<table>
<thead>
<tr>
<th>Crop</th>
<th>Area (million ha)</th>
<th>Share of total cropped area (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>145.1</td>
<td>9.7</td>
</tr>
<tr>
<td>Wheat</td>
<td>224.6</td>
<td>15.0</td>
</tr>
<tr>
<td>Coarse grains</td>
<td>325.3</td>
<td>21.7</td>
</tr>
<tr>
<td>Soybeans(^b)</td>
<td>56.5</td>
<td>3.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>751.5</strong></td>
<td><strong>50.2</strong></td>
</tr>
</tbody>
</table>

\(^a\) Total cropland is taken here to be 1.5 billion ha (FAO 1988).

\(^b\) 1988/89.

Sources: USDA (1991) for grains and USDA (1990) for soybeans.

Table 3.2 indicates that at "present" 400 million ha of cropland in use have characteristics favoring high productivity and that 200 million ha of land now in pasture and 100 million ha now in forests also have these characteristics.

The interpretation of the medium- and low-capability columns is comparable. On balance, land now in pasture and forests with high, medium and low potential for crop production totals 1.8 billion ha, 300 million ha more than the amount of land now in crops.\(^2\) Table 3.3, drawing on Table 3.2, compares the quality of potential cropland with that of land now in crops.

The comparison indicates that the quality of potential cropland is inferior, on average, to the quality of that now in crops. Nonetheless, the numbers suggest considerable potential for meeting the projected increase in global demand for food over the next several decades by converting to crop production some of the land now in pasture and forest.

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\(^2\) Buringh (1982), the source of the numbers in Table 3.2, indicates that the distinctions among high-, medium- and low- potential cropland are based on soil and climatic conditions in major regions around the world. They assume "current" technology and farm management practices.
Table 3.2: Land in Various Uses Classified by Potential for Crop Production, 1975 (million ha)

<table>
<thead>
<tr>
<th>Land Use</th>
<th>High</th>
<th>Medium</th>
<th>Low</th>
<th>Zero</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cropland</td>
<td>400</td>
<td>500</td>
<td>600</td>
<td>0</td>
<td>1500</td>
</tr>
<tr>
<td>Grassland</td>
<td>200</td>
<td>300</td>
<td>500</td>
<td>2000</td>
<td>3000</td>
</tr>
<tr>
<td>Forest land</td>
<td>100</td>
<td>300</td>
<td>400</td>
<td>3300</td>
<td>4100</td>
</tr>
<tr>
<td>Non-agricultural</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4800</td>
<td>4800</td>
</tr>
<tr>
<td>Totals</td>
<td>700</td>
<td>1100</td>
<td>1500</td>
<td>10100</td>
<td>12400</td>
</tr>
</tbody>
</table>

Source: Buringh and Dudal (1987).

Table 3.3: Distribution of Present and Potential Cropland by Quality (percent)

<table>
<thead>
<tr>
<th></th>
<th>Present</th>
<th>Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>27</td>
<td>17</td>
</tr>
<tr>
<td>Medium</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Low</td>
<td>40</td>
<td>50</td>
</tr>
</tbody>
</table>

(Based on Table 3.2).
Dudal, Higgins and Kassam (1982) estimated that, at "present" (i.e., 1970s and 1980s), there are 3031 million ha of potential cropland in the world, 1461 million of which are under cultivation. Of the 1570 million potential cropland hectares not presently cultivated, 1370 million ha -- 87 percent -- are in the LDCs. In the scenario for the growth of global food demand sketched in Chapter 2, the LDCs account for over 90 percent of the demand increase. The Dudal, Higgins and Kassam estimates that 87 percent of uncultivated potential cropland is in the less-developed world suggest to the present reviewers that, as a first approximation, much, perhaps most, of the increased demand for food in those countries could be accommodated by expanding the area in them under cultivation. The suggestion, however, probably is quite misleading for a number of reasons discussed below.

Reservations About Potential Cropland

The Distribution of Potential Cropland. One reason for thinking that the estimates of potential cropland are misleadingly high is that the land is quite unevenly distributed among LDCs, 45 percent of it being in Africa and 49 percent in South America (Table 3.4). There is no particular reason in economics why the unequal distribution of unexploited cropland in the LDCs should, per se, be an obstacle to the use of that land as a resource available to them all. In principle, the better endowed countries could export to those less favored with potentially cultivable land. But in many, perhaps most, of the LDCs, there are strong political pressures to increase the percentage of domestic food demand met by domestic production. Consequently, from the standpoints of Asian countries, a hectare of uncultivated potential cropland in Africa or South America is surely not equivalent to a hectare within their own borders. We do not expect the Asian countries to be driven to a policy of food autarchy by the land constraint in that region. Our point, rather, is that they are not likely to view the relative abundance of land in Latin America and Africa as a readily available resource to overcome their own land scarcity. Their response to that scarcity could easily result in some expansion of imports from less land-constrained regions; but it surely will include also a drive to develop more yield-increasing technologies of the sort discussed in Chapter 9.

Distance from markets. The reserves of potential cropland in Africa and South America are likely to be misleading also as indicators of land available for crop production in those areas over the next decade or so. Most of the potentially cultivable land in South America is in the humid tropics, much of it land now in forest. Compared to presently cultivated land, the potential land is far from domestic and foreign markets, and is poorly connected by road, rail and air to those markets. In Africa, this lack of transport infrastructure perhaps is even more of a constraint to

---

3Part of the difference between this estimate of potential cropland -- 1570 million ha -- and that in Table 3.2 -- 1800 million ha -- may be due to rounding. That is, Dudal, Higgins and Kassam (1982) estimate 1461 million ha "now" in crops and the Table 3.2 estimate is 1500 million ha. A check of the sources -- Dudal, Higgins and Kassam (1982) and Buringh (1982) -- does not clarify the rest of the difference. Given the very approximate nature of all of these estimates, the unexplained difference is not of major importance.
Table 3.4: Potential Cropland in the Less-Developed Countries (million ha)

<table>
<thead>
<tr>
<th></th>
<th>S.W. Africa</th>
<th>S.E. Asia</th>
<th>Central Asia</th>
<th>South America</th>
<th>Central America</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potentially Cultivable</td>
<td>789</td>
<td>48</td>
<td>297</td>
<td>127</td>
<td>819</td>
<td>2155</td>
</tr>
<tr>
<td>Presently Cultivated</td>
<td>168</td>
<td>69</td>
<td>274</td>
<td>113</td>
<td>124</td>
<td>784</td>
</tr>
<tr>
<td>Uncultivated</td>
<td>621</td>
<td>0</td>
<td>23</td>
<td>14</td>
<td>695</td>
<td>1392</td>
</tr>
<tr>
<td>% of the region</td>
<td>79</td>
<td>0</td>
<td>8</td>
<td>11</td>
<td>85</td>
<td>65</td>
</tr>
<tr>
<td>% of all regions</td>
<td>44.6</td>
<td>0</td>
<td>1.7</td>
<td>1.0</td>
<td>49.9</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Source: Calculated from Buringh and Dudal (1987) Table 2.6, p. 22.

Opening new land to crop production then in South America. According to a Consultative Group on International Agricultural Research (CGIAR) report, there are only 206,000 km of roads in the 14 landlocked countries of Africa. And the railroad system was developed in the colonial era primarily to link inland areas with ocean ports through which exports flowed out and imports flowed in. Consequently Central Africa, because of its vast distances from ocean ports, has no major rail links within the region, "in spite of its agricultural potential" (CGIAR 1988). The idea of a growth corridor based on major new highways has been canvassed, for instance, by Seckler, Gollin and Antoine (1991, p.98).

The underdevelopment of the African transport and communications infrastructure must have had much to do with the finding by Ahmed (1987) that African farmers received only 30-50 percent of the prices paid by final users of agricultural commodities, in contrast to the 75-85 percent received by Asian farmers.

In both Africa and South America, the cost of building the transport and communication infrastructure necessary to move production inputs to the regions and take production out has to be counted as part of the cost of realizing the cropland potential of the two regions. Analysis may show that these costs would be higher than the cost of increasing output by more intensive use of cropland already in production in areas of the two regions that are better connected to domestic and foreign markets.

**Opportunity costs of land conversion.** Much of the potential cropland in South America and Africa could be exploited only by clearing land now in forest. This would involve some opportunity cost measured by the value of forestry services which
conversion would foreclose. Conversion of range to crop production also would exact an economic opportunity cost in terms of lost animal production and the complementarity that this brings to cropping phase of rotations. Given the basis for the estimates of cropland potential (see footnote 2) it is clear that the estimates do not take these opportunity costs into account.

Tropical forest clearing likely could also incur environmental costs in the form of loss of biological diversity that clearing entails (Chapter 5) and of added contribution to the enhanced greenhouse effect and global warming, taken up further here in Chapter 6. These costs generally are not reflected in markets, so no one knows their present or potential future magnitude. Nonetheless, the costs are believed to be high by influential members of the world community, and widely publicized efforts are underway to persuade the Brazilian and other governments in tropical areas to slow if not halt tropical forest clearing. So far these efforts have met with little success, but there is every reason to believe they will continue. The pressure to control deforestation will mount and likely will have more effect. In this case, the realizable cropland potential of South America, and possibly Africa, would be considerably less than the numbers in Table 3.3 suggest, other things being equal.

Soil characteristics. It was pointed out above that the estimates of potential cropland in Table 3.2 indicate that land now in forest and range with potential for crop production generally is of lower average quality than land already in crops. The estimates of potential cropland are based on soil and climatic conditions characterizing the land (see footnote 2 above). The lower average quality of the potential cropland in Table 3.2 thus indicates that the combination of climate and soil characteristics of that land is less favorable for crop production than the characteristics for land currently in production. Within the constraints of this study there is no way of separating the soil constraint from the climate constraint applying to potential cropland. The discussion here of soil constraints may, therefore, apply as much to land already in crop production as it does to potential cropland. Since most of the potential cropland is in (tropical) South America and Africa, land quality in those regions is especially relevant.

Table 3.5 shows estimates of the quantities of different soils in the tropics and in the semiarid tropics of Africa and Latin America. The three soil orders, Oxisols, Alfisols and Ultisols, account for over 55 percent of the tropical soils and for 46 percent and 47 percent, respectively, of the soils in the semiarid tropics of Africa and Latin America. Stewart, Lal and El-Swaify (1991), perhaps controversially, describe these as "low-activity clay" soils, and Lal (1984, p. 76) says of such soils that they "exhibit little swell-shrink capacity. On drying, most of these soils become hard and have unusually high strength ... ", which inhibits seedling emergence.

Table 3.5 indicates that Aridisols account for 21 percent of tropical soils and 30 percent and 14 percent, respectively, in the semiarid tropics of Africa and Latin America. Stewart, Lal and El-Swaify (1991, p. 131) write of these soils that they are relatively low in organic matter and that in most years, their moisture content is inadequate to mature a crop without irrigation.
Table 3.5: Land Area in Different Soils in the Tropics and in the Semi-Arid Tropics of Africa and Latin America

(million ha)

<table>
<thead>
<tr>
<th>Soil Order</th>
<th>Tropics</th>
<th>Semiarid tropics of Africa</th>
<th>Latin America</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfisols</td>
<td>800</td>
<td>466</td>
<td>107</td>
</tr>
<tr>
<td>Aridisols</td>
<td>900</td>
<td>440</td>
<td>33</td>
</tr>
<tr>
<td>Entisols</td>
<td>400</td>
<td>255</td>
<td>17</td>
</tr>
<tr>
<td>Inceptisols</td>
<td>400</td>
<td>38</td>
<td>-</td>
</tr>
<tr>
<td>Mollisols</td>
<td>50</td>
<td>-</td>
<td>78</td>
</tr>
<tr>
<td>Oxisols</td>
<td>1100</td>
<td>188</td>
<td>-</td>
</tr>
<tr>
<td>Ultisols</td>
<td>550</td>
<td>24</td>
<td>8</td>
</tr>
<tr>
<td>Vertisols</td>
<td>100</td>
<td>51</td>
<td>-</td>
</tr>
<tr>
<td>Totals</td>
<td>4300</td>
<td>1462</td>
<td>243</td>
</tr>
</tbody>
</table>

Source: Adapted from Stewart, Lal and El-Swaify (1991, Table 3.3, p. 132). For a brief description of the soil orders, see the text.

Writing of tropical soils generally, Lal (1984, p. 77) notes that after a "relatively long period of natural or planted fallow" the organic matter content of the surface layer of these soils is comparable to that in temperate region soils. However, the organic matter in tropical soils typically is concentrated in the top 5 to 10 cm. With land clearing, the soil organic matter is oxidized at a rate about 4 times faster than in temperate zone soils, and declines sharply in as little as 2 or 3 years. This is particularly significant for the low-activity clay soils, such as the Oxisols, Alfisols and Ultisols, because in these soils

"... organic matter plays a very important role in improving structural stability, decreasing compactibility, improving soil available water and nutrient resources, decreasing leaching losses, and enhancing biological activity of soil fauna (e.g., earthworms, etc.)" Lal (1984, pp. 77-8).

Lal (1986) developed a three-point rating system for classifying the principal tropical soils according to factors that limit their productivity in cultivation. Table 3.6 shows this classification system. With the exception of trafficability and
Table 3.6: Soil-Related Constraints to Use of Tropical Soils for Cultivation

<table>
<thead>
<tr>
<th></th>
<th>Oxisols</th>
<th>Ultisols</th>
<th>Alfisols</th>
<th>Inceptisols</th>
<th>Vertisols</th>
<th>Mollisols</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erosion</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Compaction</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Crusting</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Drought</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Shallow rooting depth</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Trafficability</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>2/3</td>
</tr>
<tr>
<td>Supraoptimal soil temperatures</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Chemical/nutritional status</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2/3</td>
</tr>
</tbody>
</table>


Note: 3 is severe, 2 is moderate and 1 is slight.

Chemical/nutritional status, productivity of the Alfisols is seriously constrained for cultivation. These soils make up 19 percent of all tropical soils (Table 3.5). The Oxisols and Ultisols, which jointly account for another 38 percent of all tropical soils, are severely-to-moderately constrained by all the factors except soil crusting and trafficability.

Note that the least constrained soils, the Mollisols, account for only 50 million ha in the tropics (a little over 1 percent of the total). In the United States the 232 million ha of Mollisols make up 26 percent of the total (Stewart, Lal and El-Swaify, 1991, p. 132).

Disease as an obstacle. It is widely held that diseases affecting both humans and animals inhibit the development of potential cropland in Africa and Latin America. Much of the discussion of this issue focuses on the tsetse fly, the major carrier of Trypanosomiasis, a serious disease affecting both animals and people particularly, but not exclusively, in Africa. (In people the disease is commonly called sleeping sickness). In 1963, the FAO published a study of tsetse fly infestation in Africa in which it was estimated that some 10 million km² of land in the central part of the continent were affected. A major consequence was that the cattle population in the region was far less than it would have been in the absence of infestation. Subsequent studies have produced estimates of the infested area very similar to those of the FAO (e.g., Jahnke 1982).

Although the threat of the tsetse fly is primarily to cattle, it nonetheless could inhibit conversion of land to crop production because much of African agriculture is
built on an intimate relationship of animals to crops, with animals in some situations providing the mode of tilling the land, in others providing meat and milk. Consequently, where cattle are banned by the threat of the tsetse fly, crop production is likely to be inhibited (Ruthenberg 1980).

Although the view is widely held that tsetse fly infestation effectively puts large areas of Africa off limits for animal and crop production, there is increasing evidence that this view needs modification. First, increasing population pressure leads to the destruction of the savannah-shrub vegetation, the habitat of the most widespread tsetse sub-group (Glossina morsitans). Experience suggests that flies of this sub-group virtually disappear when population exceeds 40 inhabitants/km$^2$ (Jordan 1988). Second, simple non-polluting technologies are becoming available to control the fly. Fly traps and screens impregnated with non-polluting insecticides, and fly repellents applied directly to the animals have been shown to protect herds in high-tsetse-challenge environments (Cuisance 1991). Third, the combination of increased availability of trypanocidal pharmaceuticals and acquired resistance allow animals of trypano-sensitive breeds to survive in a tsetse environment. At least 40 million cattle of such trypano-sensitive breeds can now be found in tsetse infested zones (Winrock 1992). Thus, as population pressure increases and improved technologies become available, this 10 million kms can potentially be converted into crop land. However, the eco-system in the sub-humid tsetse-infested zone of Sub-Saharan Africa is extremely fragile, with few pockets of good land (Omerod 1986). Thus, it raises a question about the reliability of the estimates of potential cropland in Africa shown in Table 3.3 above.

**Loss of land to urbanization.** A literature search reveals very little information about the amount of land in urban and other built-up uses on either regional or global scales. The World Resources Institute (1988) publishes data on the amounts of such land in a few countries, but most of the world is left out. Buringh and Dudal (1987), drawing on Buringh (1982), gives a global estimate of some 400 million ha of "non-agricultural" land in the 1970s and 1980s. Although Buringh and Dudal do not precisely define non-agricultural land, the 400 million ha evidently includes much land other than that in urban and built-up uses. This can be inferred from the fact that, when the 400 million ha number is used to calculate the amount of urban land per person living in urban areas in the world, the result is 0.18, which is completely inconsistent with other data showing land per person in major cities of the world. The city data vary from 0.013 ha/person in Buenos Aires to 0.002 in Lagos. (The city data are reported in World Resources Institute 1987, p. 264).

We concluded that the city data showing urban land per urban person are more reliable than the global estimate that can be computed from Buringh and Dudal (1987). We also concluded that the issue of agricultural land conversion would be more important in the less-developed than in the MDCs because of both faster urban population growth and faster growth in demand for food in the LDCs. We decided, therefore, to use the urban population density data for the LDCs as a guide in estimating how much land might be converted to urban uses over the period to 2030. The numbers in the range noted, however, reflect conditions in the largest cities in the
various countries. There is some evidence that land use per capita in smaller urban areas is greater than in the largest cities. In the USA, for example, urban land per urban person in the country as a whole is about 0.13/ha, far higher than in New York or Chicago. Data compiled by the World Resources Institute (1988, p. 268) suggest that, in LDCs also, population density is less across urban areas as a whole than in the largest cities. In Pakistan, for example, the amount of "built-up and settled" land was 1.6 million ha in 1980 (World Resources Institute 1988, p. 268). Assuming that this was urban land and that 25 percent of Pakistan's population was urban in this sense in 1980, then there were 0.08 ha of urban land per urban person in the country as a whole. In Karachi, the land per capita figure was 0.008.

To arrive at an estimate of future urban land use per capita in the LDCs, we decided to use a figure of 0.05 ha. This figure is higher by a good margin than those for any of the major cities shown in World Resources Institute (1987), but it reflects our belief that population density in those cities is greater than in urban areas as a whole. The 0.05 estimate also assumes that the percentage distribution of new urban populations in the future will be about the same as at present. We believe that the estimate is more likely to be too high than too low. We use it nonetheless because, for purposes of this study, we believe it better to overestimate land conversion than to underestimate it. In addition, the amount of urban land per person in the future might be higher than the current average if more future urban growth is in smaller towns and cities. To the extent that growth occurs in larger cities, however, the hectare per person figure likely would decline from the present average.

Table 3.7 shows projections of the global urban population for MDCs and LDCs. As indicated above, we believe the conversion issue will not be very important in the MDCs. Accordingly, we deal here with the issue in the LDCs. Assuming that 0.05 ha of land will be required for each of the additional urban people in those countries, then the amount of additional land needed to accommodate the projected 2488 million increase in less-developed country urban population from 1990 to 2025 would be 125 million ha. Table 3.4 above shows 1392 million ha of potential cropland in the LDCs. The projected additional 125 million ha of land needed in these countries for urban and built-up uses by 2025 would be of the order of 10 percent of the countries' potential cropland. However, not all the land converted to urban and built-up uses would be potential cropland. Consequently, the amount of such land converted would probably be less than 10 percent of the current stock of potential cropland in the LDCs.

This number, however, surely under-represents the future competition for land of urban growth with agriculture. For the reasons already discussed, the 1392 million ha must substantially overstate the amount of land now in forest and range which would be converted to crop production at acceptable economic and environmental costs. Nevertheless, even if the amount of potential cropland is only half the 1392 million ha estimate, the 125 million ha projected for urban expansion would be less than 20 percent of potential cropland. It seems fair to conclude that taking the LDCs

\[4\text{Independently of our work, it seems that others have also developed an estimate of 0.05 people/ha of urban land in the LDCs (FAO/IIASA/UNFPA 1982, pp. 17-18).}\]
Table 3.7: Projections of Urban Populations in More- and Less-Developed Countries (millions)

<table>
<thead>
<tr>
<th></th>
<th>1990</th>
<th>2010</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>More-developed countries</td>
<td>877</td>
<td>1011</td>
<td>1087</td>
</tr>
<tr>
<td>Less-developed countries</td>
<td>1357</td>
<td>2612</td>
<td>3845</td>
</tr>
<tr>
<td>Africa</td>
<td>210</td>
<td>528</td>
<td>894</td>
</tr>
<tr>
<td>Caribbean and Central America</td>
<td>100</td>
<td>167</td>
<td>221</td>
</tr>
<tr>
<td>Temperate South America</td>
<td>42</td>
<td>56</td>
<td>64</td>
</tr>
<tr>
<td>Tropical South America</td>
<td>184</td>
<td>293</td>
<td>370</td>
</tr>
<tr>
<td>East Asia (ex Japan)</td>
<td>296</td>
<td>513</td>
<td>743</td>
</tr>
<tr>
<td>South Asia</td>
<td>524</td>
<td>1052</td>
<td>1548</td>
</tr>
<tr>
<td>All countries</td>
<td>2234</td>
<td>3623</td>
<td>4932</td>
</tr>
</tbody>
</table>


as a whole, the conversion of land to urban and built-up uses over the next several decades is not likely to seriously diminish the supply of land for agricultural production.

The conclusion is only a first approximation, however, because it leaves out of account the fact that both the projected urban demand for land and the quantities of present and potential cropland vary so widely across the LDCs. Table 3.7 indicates that almost 60 percent of the projected increase in urban populations in the LDCs from 1990 to 2025 -- 1471 million out of 2488 million -- would be in densely populated East and South Asia and only about 40 percent (1017 million) would be in lightly populated Africa and Latin America. More specifically, the 1471 million population increase in East and South Asia would take an additional 75 million ha of land (using again the 0.05 estimate of per capita land use in urban areas). This would represent about two-times the 37 million ha of presently uncultivated land with crop potential in Asia (Table 3.4)! By contrast, the 1017 million urban population increase in Africa and Latin America would take 50 million ha, less than five percent of the 1355 million ha of potential cropland in those regions.

These comparisons must not be pressed too hard, not only because of uncertainties about the data and the projections of urban population but also because mere numbers of hectares of present and potential cropland tell nothing about the technical, economic and institutional conditions which convert the numbers into estimates of the supply of agricultural land. Nevertheless, the data and related
discussion provide reasonably strong support for three generalizations: (a) over the next several decades, the conversion of land to urban and built-up user is not likely to limit the supply of agricultural land in LDCs as a whole; (b) but conversion could press heavily on the supply of agricultural land in Asia; (c) African and Latin American countries should be able to accommodate demands for urban land without seriously depleting the supply available for agriculture. Drawing on the earlier argument about the political importance of increasing food self-sufficiency in LDCs, we add another generalization: (d) whatever the technical, economic and institutional conditions of agricultural land demand and supply around the world, Asian countries are not likely to view the relative abundance of land in Africa and Latin America as an easy substitute for the increasing scarcity of their land resources. This suggests that pressure to develop land-saving agricultural technologies will be much higher in Asia than in Africa and Latin America.

Summary on the Quantity of Land

Although available estimates indicate that, on a global scale, the quantity of land now in range and forest with potential for crop production is about equal to, or somewhat greater than, the quantity of land now in crops, these numbers overstate the feasibility of meeting future global demands for food by bringing more land under crops. Most of the estimated potential cropland is in the LDCs, a generally favorable condition, because most of the increased demand for crop output over the next several decades will be in those countries. However, most of the potential land is in Africa and Latin America while a major part of the demand increase will be in Asia. Political pressures for increasing food self-sufficiency in Asian countries suggest that those countries will not view potential cropland in Africa and Latin America as reserves on which they can draw to the extent that strictly economic conditions might indicate. Most Asian countries now view their agricultural land supplies as severely constrained. The apparent relative abundance of land in Africa and Latin America is not likely to change this.

Relative to land now in crop production, much of the potential cropland in South America and Africa is distant from domestic and foreign markets. And in both regions the transport and communications infrastructure necessary for trade between the areas of cropland potential and elsewhere is poorly developed.

It is clear that the estimates of potential cropland do not take into account the opportunity costs of converting range and forest land to crop production. In the case of forests, clearing is widely and properly viewed as exacting a high opportunity cost in losses of global biological diversity. Although evidence is insufficient to judge the validity of this view, it nonetheless creates pressure on governments in tropical countries to limit if not halt further forest clearing. The estimates of potential cropland indicate that this land is of lower average quality than land now in crop production. Studies of the productive properties of tropical soils -- most of the potential cropland is in the tropics -- indicate that these soils are indeed of lower inherent productivity than most temperate-zone soils.
Although human and animal diseases -- trypanosomiasis transmitted by tsetse fly in Africa gets most attention -- are widely held to limit the development of potential cropland in Africa and South America, the view is open to question. Evidence from Africa with respect to the tsetse fly suggests that the poor quality of much of the land is the limiting factor to crop production, not the tsetse fly. This argument is a direct challenge not only to the conventional wisdom about the role of the tsetse fly, but also to such estimates of cropland potential in Africa as those shown in Table 3.4.

Conversion of land to urban and other built-up uses reduces the amount of land that might otherwise be available to agriculture. Projections of population growth, combined with the very limited data on land now in urban and other built-up uses, suggests that conversion of land to these uses is not likely seriously to constrain the supply of agricultural land in the MDCs. The prospective situation is more problematical in the LDCs. Although projected conversions would take a small percentage of the potential cropland in Africa and Asia as measured by the numbers in Table 3.3, the previously discussed reservations about the validity of those numbers suggests that the impact of future urbanization on cropland potential would be greater than the small projected conversion percentage would indicate. In Asia, where the amount of potential cropland is small and the projected increase in urban population is large, the threat of urbanization to future cropland supply is clearly greater than in Africa and Latin America.

The view is widely held among analysts of world agricultural development that most of all future increases in output must come from improvements in the productivity of land already in production. Our assessment of the quantity of potential cropland is in general agreement with this position but there may be a significant difference in detail.

More specifically, our judgment is that only some 25 or more percent of the roughly 100 percent increase in global crop demand over the next four decades could be accommodated by bringing more land into crop production (see Table 9.1 and the related discussion in Chapter 9). This is consistent with our argument that the available estimates of potential cropland greatly exaggerate the amount of land that, in fact, could be profitably converted to crop production at "acceptable" costs. It is consistent also with the assertion that "most" future increases in global crop production must come from increased yields. Nevertheless, our estimate is rather higher than the present consensus view on the subject.

The Quality of Land: Land Degradation

Because the quantity and quality of land are so interrelated in determining land supply, the preceding discussion of land quantity necessarily dealt to some extent with land quality. The focus was on the productive capacity of soils believed to have future potential for crop production. This section takes a broader view of land quality, discussing land presently in crops as well as that with crop potential, and taking account of the effects of cropping and grazing practices on the present and future productive capacity of the land.
Much of the literature discusses land degradation under the rubric of desertification. We discuss some definitions of desertification, but believe the word can be misleading so subsequently we use land degradation to embrace the various processes through which land loses productivity.

Definitions of Desertification

Definitions of desertification vary in detail but central to all of them are processes that result in the long-term losses of land productivity. Dregne (1983), quoted in Bie (1990), defines desertification as

"...the impoverishment of the terrestrial ecosystem under the impact of man. It is the process of deterioration in these ecosystems that can be measured by reduced productivity of desired plants, undesirable alterations in the biomass and the diversity of the micro- and macro-fauna and flora, accelerated soil deterioration and increased hazards for human occupancy."

Mabbutt (1984, p. 103) defined desertification as the

"...diminution or destruction of the land [that] can lead ultimately to desert-like conditions".

Mabbutt’s study was focused on "the arid, semi-arid and sub-humid, and productive, parts of the hyper-arid climate zones of low and variable rainfall" which are drought prone and "vulnerable to deterioration through excessive pressure of man’s use" (Mabbutt 1984, p. 104).

For Gorse and Steeds (1987) desertification is

"...the sustained decline of the biological productivity of arid and semi-arid land (p. iii) ..." resulting in an impoverished soil that is irrecuperable" (p. ix).

Nelson (1988) defines desertification as sustained degradation of soil productivity and vegetative cover in arid, semi-arid and dry sub-humid areas, caused at least partly by man, and that can neither be easily reversed by removing the cause nor easily reclaimed without substantial investment.

Of the four definitions, Dregne’s is most comprehensive, indicating explicitly, unlike the other three, that desertification includes the loss of biological diversity of both plants and animals. This feature, however, appears to be implicit in the definitions of Mabbutt and Gorse/Steeds.

Dregne and Mabbutt include only man-made deterioration in their definitions, Nelson includes both human and natural forces, and Gorse/Steeds are silent on this issue. They note, however, that the question of whether desertification is man-made
or the result of natural climatic variation is hotly disputed. We prefer a definition that includes human effects, but in any case the dispute is of little consequence for our purposes. To the extent that desertification is natural, something surely can be done, in principle, to adjust to it. To the extent that it is manmade, something surely can be done to control it. In either case, there is a potential agenda of social action to deal with the problem.

Gorse and Steeds confine desertification to arid and semi-arid land; Nelson and Mabbutt include these lands as well as those in dry sub-humid areas; and Dregne, by implication, includes all agro-climatic zones in his definition. Although the word desertification, in common parlance, suggests a definition similar to those of Gorse/Steed, Nelson, and Mabbutt, we here use that of Dregne because we want to assess the productivity effects of agricultural land degradation, wherever they may occur.

Under this broad definition, desertification includes not only the land-productivity effects of desert encroachment, the obvious case, but also soil productivity losses because of wind and water erosion, soil compaction and crusting, and soil salinization and waterlogging, mainly, but not exclusively, on irrigated land in arid and semi-arid areas. (We do not deal with salinization and waterlogging here, but include them in Chapter 4 dealing with water resources.)

As noted in the lead to this subsection, to many people, desertification means the encroachment of deserts, a relatively unimportant source of land productivity loss. We prefer land degradation to describe these several processes and use that expression henceforth.

When is Land Degradation a Problem?

Our concern throughout this paper is with the capacity of the global agricultural system to increase food and fiber production in response to long-term increases in global demand at economic and environmental costs that people around the world will find socially acceptable. From this perspective, land degradation becomes a problem when it threatens to impose unacceptably high costs on people in present or subsequent generations. The answer to the question of when do costs become unacceptably high would depend in good part on one's assumptions about the possibilities of trade in food and fiber among regions. The more extensive and robust the trading system, the greater the capacity of regions to avoid rising costs of degrading their natural resources by substituting imports for domestic production. This, of course, is not to say that resource degradation is unimportant. It is to say that not all degradation is equally important, and some may not be very important at all, depending on the trading possibilities.

It was noted in Chapter 2 that, for many countries, trading possibilities are constrained not only by the economics of pure comparative advantage but also by a host of political considerations reflected in trade policies, e.g., a drive to increase self-sufficiency in food and fiber production. The stronger this drive figures in the politics
of the country, the more important that the country limit degradation of its natural resources used in agricultural production.

This argument is directly relevant to the question of when is land degradation a problem. The point of the argument is that the question cannot be answered for any region, however small or large, without taking account of the region’s willingness to use its opportunities for trading with other regions. The more ample those opportunities and the greater the willingness of the region to use them, the less likely that land degradation will be a problem for the region.

It follows that, even if we were able to quantify the economic and environmental costs of land degradation in all the places where it occurs around the world -- which we are not -- we still would not be able to fully assess the importance of land degradation as a problem. This in no way denies the importance of quantitatively assessing the costs of land degradation. But it asserts that such an assessment would take us only part way toward an answer to the question of land degradation’s importance at whatever spatial scale, from the smallest region to the world as a whole.

**Extent of Land Degradation**

A review of the literature on land degradation reveals two seemingly contradictory themes. One is deep concern about the consequences of land degradation for the sustainability of the global agricultural system, particularly that part of it in the LDCs. The other theme is how little reliable information there is about how much land degradation is occurring, let alone its consequences for productivity.

The first theme was given impetus by a report prepared for the United Nations conference on desertification held in Nairobi in 1977. The theme found support also in Mabbutt’s (1984) paper which was a follow-up to the study for the desertification conference. Mabbutt’s paper, which used desertification where we would use degradation, was based on a survey questionnaire sent in 1982 to government officials in "all countries affected by desertification" (Mabbutt 1984, p. 103). The survey collected information about changes in population, land-use, and crop and livestock productivity in the dryland areas since 1977, and on the status and trends in those areas. In addition to the survey, Mabbutt also collected land degradation information from the United Nations regional commissions, including the Sudano-Sahelian Office.

As indicators of land degradation the questionnaire specified growth and encroachment of mobile dunes and aeolian sandsheets; deterioration of rangelands; degradation of rainfed cropland; waterlogging and salinization of irrigated land; deforestation and destruction of woody vegetation; and declining quantity and quality of ground and surface water supplies.

Respondents to the questionnaire were asked to indicate amounts of land that were moderately desertified (loss of up to 25 percent of the productive potential of the
land), severely desertified (25-50 percent loss of productivity) and very severely desertified (loss greater than 50 percent).

The results of the survey provided estimates of both the total amount of land degradation around the world, as well as its rate of change. With respect to the latter, the results were interpreted as showing that the productivity of approximately 20 million ha was being reduced to zero annually, another 6 million ha were converted to "wasteland", and in 1982 the number of people living in desertified areas had increased 35 percent since the study for the 1977 land degradation conference.

With respect to the total amount of land degradation, the survey showed that 4.5 billion ha (about 35 percent of the earth's land surface) suffers some degree of degradation, and that more than 850 million people are in these areas. Of the 4.5 billion ha, 3475 million ha was drylands already at least moderately degraded. This is 75 percent of all productive land in the world's drylands (Mabbutt 1984, p. 105). Of the 3475 million ha, 3100 million was rangelands (80 percent of dry rangeland), 335 million was rainfed cropland (60 percent of rainfed dry cropland) and 40 million was irrigated land (30 percent of irrigated dryland). Of the 3100 million ha of degraded dry rangeland, 1300 million ha was severely to very severely degraded. This was true also of 170 million ha of the 335 million ha of degraded dry rainfed cropland, and of 13 million of the 40 million ha of degraded dry irrigated land.

The survey results showed further that the regions most affected by land degradation, in descending order, were the Sudano-Sahelian, Africa south of this region and South Asia. The threat was perceived to be most serious on rainfed croplands because this affects the most people and has the potential eventually to degrade the land to the point of "irreversible destruction" (Mabbutt 1984, p.108). The threat to rainfed cropland was seen as less severe in temperate zones of both less- and more-developed countries.

Nelson (1988) surveyed the evidence for the extent of land degradation, including Mabbutt’s study, as well as one by Lamprey (1975) of land degradation in the Sudan. Nelson pointed out that the meanings of moderately, severely, and very severely degraded, as used in Mabbutt’s questionnaire, are subject to varying interpretations. In addition, the time of the survey, 1982, was at the end of a severe and prolonged drought in Africa, which could have affected the judgment of African officials about the extent and severity of land degradation. Nelson also notes that the Mabbutt study included sub-humid areas, which were not included in the study for the 1977 desertification conference. This imparts some ambiguities to Mabbutt’s finding that the number of people living in degraded areas increased 35 percent between 1977 and 1982.

The study of the Sudan by Lamprey (1975) apparently was the source for the widely-cited estimate "that the Sahara desert is advancing south at 5.5 km/y" (Nelson 1988, p.6). Nelson’s literature review brought this estimate into question. A study by Hellden (1984) found "...no creation of long-lasting desert-like conditions during the 1962-1979 period in the area [Kardofan, Sudan] ... of the magnitude" generally accepted by the Sudanese government and international organizations. "The impact
of the Sahelian drought was short-lasting followed by a fast land-production recovery" (Nelson 1988, p. 6).

Writing about the same area, Olsson (1984, as reported by Nelson) found no elimination of woody species, no southward shift of ecological zones, and that the boundaries between different vegetation associations appear to be the same now as they were 80 years ago.

Nelson reports a study in India, based on remote sensing data, which found no evidence that, between 1958 and 1976, the Rajasthan desert had spread toward the Delhi-Mathura-Agra region. The study did conclude, however, that 4.35 percent of western Rajasthan overall had been affected by land degradation.

Of two studies in Niger reviewed by Nelson, one found evidence of land degradation and the other did not. A study done in 1982 in Australia concluded that 35 percent of the country's arid lands were "affected" by land degradation. Another study done in the same year in western New South Wales, one of the important pastoral areas in Australia, found that, since the mid-1970s, there was remarkable recovery from previous drought throughout the region.

Nelson draws a number of general conclusions from his review of the literature on land degradation.

(a) The extent and severity of land degradation are not as well known as commonly believed. The evidence on this is "extraordinarily skimpy" (Nelson 1988, p.1).

(b) The extent of professional agreement about the extent and causes of land degradation, and about solutions to it, is generally overestimated.

(c) The irreversibility of land degradation processes probably is overestimated, although serious losses have occurred in some areas.

(d) The image of land degradation too often is one of advancing sands instead of, more properly, one of "pulsating deteriorations", sometimes with reversals or at least long-term remissions.

Nelson's paper illustrates the theme that little is known about the extent and severity of land degradation. Dregne (1988, p. 679) notes that estimates of land degradation, including his own, are based on "... little data and much informed opinion". Writing specifically of soil erosion and its productivity effects, Dregne (1988, p. 680) asserts that "there is an abysmal lack of knowledge of where water and wind erosion have adversely affected crop yields". He notes that the equations for calculating wind and water erosion were developed for use in the temperate zone (more specifically, the American midwest) and their accuracy for the tropics is uncertain.
El-Swaify, Dangler and Armstrong (1982, p.1), authors of the most comprehensive published study of soil erosion in LDCs, assert that "... there is little or no documentation of the extent, impact or causes of erosion..." in tropical environments. Lal and Okigbo (1990) share these several views about the lack of reliable land degradation data. They note, with respect to Nigeria, that most of the evidence on soil degradation is from analysis of soil sampled from experiments at research stations. "There is little, if any, research done on farmers’ fields to provide concrete and reliable quantitative information on the rate, extent and distribution of soil degradation" (Lal and Okigbo 1990, p. 7).

Writing of northern Nigeria, Mortimore (1989, p.15), notes that serious erosion is easily observable in some parts of the region, but that because of the lack of good data "...the impact of erosion processes, and the projection of their impact in the future must be guesswork." Mortimore also notes that there is a broad and deep consensus among government officials and villagers in northern Nigeria that land degradation is pervasive but little hard evidence to support this perception. People in the area also stress overstocking of rangeland as promoting land degradation, but Mortimore (p.10) observed that these statements frequently were made "on the basis of subjective estimates of carrying capacity." Although livestock producers talked of deteriorating range, they generally attributed it to lack of rain rather than overstocking of animals. Mortimore (p. 10) concluded that it would be premature to judge from the available field evidence that rangeland deterioration was irreversible.

Oldeman, Hakkeling and Sombroek (1991) prepared a map, with an accompanying explanatory text, showing the state of human-induced degradation of the world’s soils. The map covers the land surface between 72 degrees north and 57 degrees south, an area of 13,013 million ha (Oldeman et al. 1991, p. 27). The map is designed as a Mercator projection so the scale varies from 1:15M at the equator to 1:10M at 48° latitude to 1:5M at 70° latitude (Oldeman et al. p.6).

The map represents four kinds of soil degradation: water erosion, wind erosion, chemical degradation (loss of nutrients, soil salinization, urban-industrial pollution, and acidification) and physical degradation (compaction, waterlogging and subsidence of organic soils). The total degraded area is assessed as 1964 million ha, 15 percent of the total mapped area of 13,013 million ha. Water erosion accounts for 56 percent of the 1964 million degraded hectares, wind erosion for 28 percent, chemical degradation for 12 percent and physical degradation for 4 percent.

Four degrees of soil degradation were defined and are here paraphrased:

(a) Light: somewhat reduced agricultural productivity; restoration to full productivity is possible with changes in the management system, original biotic functions still largely intact.

(b) Moderate: greatly reduced agricultural productivity; restoration only with major improvements; original biotic functions partially destroyed.
(c) Strong: land is not reclaimable at the farm level; major engineering works would be required for restoration; original biotic function largely destroyed.

(d) Extreme: agriculture productivity wholly lost and beyond restoration; original biotic function completely destroyed.

Of the 1964 million ha judged degraded by human action, 38 percent is assessed lightly degraded, 46 percent is moderately degraded, 15 percent is strongly degraded and 0.5 percent is extremely degraded.

The map also depicts four levels of severity of land degradation: low, medium, high and very high. Severity depends on the degree and areal extent of degradation within individual mapping units. For example, a mapping unit within which 0-4.9 percent of the land is moderately degraded has low severity of degradation. If the area of moderately degraded land is 5-9.9 percent of the total area the land has medium severity of degradation. It has high severity of degradation if 10-49 percent of the area is moderately degraded and very high severity of degradation if the moderately degraded land is 50 percent or more of the total area of the mapping unit.

The work of Oldeman et al. (1991) clearly is a significant advance in the ongoing effort to get a global perspective on the extent and severity of soil degradation. Yet the meaning of "degradation" as used by Olderman et al. is, to us, somewhat unclear, making it difficult to interpret their results. Their map shows, for example, that, in the USA most of the land in the states of Illinois, Iowa, Kansas, Nebraska, South and North Dakota is in the high severity of degradation category. That is, 10-49 percent of the land in these states is classified as moderately degraded. The reason offered is agriculturally induced water and wind erosion. Recall the definition of moderate degradation: greatly reduced productivity; restoration only with major improvements; original biotic functions partially destroyed.

The problem with this is that, in the six states, yields of maize, wheat, soybeans and sorghum, the principal crops, have risen steadily over the past 40 years. The yield increases reflected higher yielding crop varieties, greatly increased per hectare use of fertilizers and pesticides, more irrigation, and improvement in management. Some degree of erosion-induced loss of soil productivity may have occurred over this period. In fact, a study by Crosson and Stout (1983) showed that, because of erosion, maize and soybean yields in the early 1980s were 2 or 3 percent less than they would have been in the absence of erosion. However, the yield experience in the six states since the early 1950s seems clearly inconsistent with the description of their soils as having suffered "greatly reduced agricultural productivity" which could be restored only with "major improvements". Moreover, other studies, cited below, indicate that continuation of cropland erosion at present rates for 100 years in that part of the USA would reduce crop yields only 3-10 percent below what they would be without erosion.

We are unable to investigate whether there may be similar anomalies in other regions between actual yield experience and the severity of soil degradation as indicated on the map prepared by Oldeman et al. More research to further advance the
initiative represented by Oldeman et al. will have great value in adding to knowledge in this important area.

**Soil erosion effects on productivity.** The work by Oldeman et al. (1991) indicates that erosion by water and wind is by far the most important source of land degradation. Other research in this area points to the same conclusion. Very little research has been done, however, to quantitatively estimate the effects of erosion on soil productivity. Stocking (1984), after systematically reviewing this research, concluded that almost all of it had been done in the United States. Although Stocking's conclusion still is valid, some research on erosion and productivity in other countries has been published since he wrote.

Before the late 1970s, all of the research in the U.S. on erosion-productivity relationships was conducted on small experimental plots. Varying amounts of topsoil were removed from one set of plots and the yields obtained were compared with those on a set of uneroded plots, both sets being cultivated with the same technologies, under the same climate conditions, and on the same soils. The crops typically were maize or wheat. The results of these experiments invariably showed that removal of topsoil reduced yields. It also was discovered, however, that on plots where the subsoil was not dramatically different from the topsoil and soil water-holding capacity was not seriously diminished, yields on the eroded plots often could be restored to their initial level with the application of fertilizer to replace natural soil nutrients.

Suggestive though they were, the U.S. studies on experimental plots were too small-scale and too localized to yield estimates of the effects of erosion on soil productivity on a national scale. Meanwhile, from the 1940s through the 1980s, American agriculture experienced a technological revolution that, among other things, produced unprecedentedly rapid increases in crop yields. Areas which in the 1930s were described by Hugh Hammond Bennett, the first Chief of the U.S. Soil Conservation Service, as "totally destroyed" for crop production by erosion shared fully in these yield increases. It appears either that Bennett was mistaken about the severity of the erosion effect, or about its permanence, or both.5

In 1977 the U.S. Soil Conservation Service conducted the first comprehensive, statistically reliable survey of the amount of soil erosion occurring annually in the United States. The survey, with more intensive sampling, was repeated in 1982 and again, with less intensive sampling, in 1987. The surveys covered sheet and rill (water) and wind erosion on cropland, pasture, range and forest land. Gully erosion was not included. The 1977 and 1982 surveys showed about the same amounts of erosion per hectare, and the 1987 survey showed a small decline.

The 1977 and 1982 surveys provided the kind of data needed to make the first reasonably reliable estimates of the effects of soil erosion on soil productivity, for

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5This experience of American agriculture and the behavior of yields is described at greater length in Crosson (1991).
major regions and for the country as a whole. Three models were developed to do this, the Productivity Index (PI) model (Larson, Pierce and Dowdy 1983; Pierce et al. 1984), Erosion Productivity Impact Calculator (EPIC) (Alt, Osborn and Colaccio 1989) and a third model developed at Resources for the Future (RFF) (Crosson 1986). PI and EPIC simulate the responses of crop growth to changes in soil characteristics -- pH, water-holding capacity, nutrient supply, bulk density, etc. -- under the impact of soil erosion. The RFF model is a regression type which accounts for intercounty differences in crop yields among a sample of counties in the Midwest as a function of intercounty differences in soil erosion, soil depth, fertilizer application, and other inputs.

Working with EPIC, Alt, Osborn and Colaccio (1989) estimated that, if cropland erosion in the United States were to continue at 1982 rates for 100 years, national average yields at the end of the period would be about 3 percent less than they would be in the absence of erosion. Pierce et al. (1984) used the PI model to estimate the effect on yields of maize on 40 million ha of cropland in the midwest under the same erosion conditions and got a 4 percent yield decline at the end of 100 years. Crosson (1986) used the RFF model to estimate the effect of 100 years of 1982 erosion on maize, wheat and soybean yields in the midwest. He found that maize and soybean yields would be 5 percent and 10 percent less, respectively, after 100 years than they would be in the absence of erosion. Wheat yields would be unaffected.

Two features of this research stand out. One is the close similarity of the results, particularly in view of the quite different modeling approaches taken. (EPIC is a far more complex model than PI). The second notable feature is the smallness of the erosion effect on soil productivity, even after 100 years at rates which the Soil Conservation Service officially regards as too high on close to one-half of the nation’s cropland. (The SCS comes to that judgment because erosion on that land exceeds 11 t/ha/y, the maximum amount consistent with maintaining the long-term productivity of the soil, according to a long-held SCS standard).

Erosion as a productivity problem now gets much less attention in the United States than it did 10 or 15 years ago. It is too much to attribute this to the results of the modeling work described above. The re-emergence of crop surpluses in the 1980s probably had more to do with the declining public interest in the problem. Nevertheless, the modeling work, and the experience of the past 50 years suggests that erosion is not now a serious threat to agricultural productivity in the United States. This is not to denigrate the work of the U.S. Soil Conservation Service. On the contrary, the work of the Service in getting soil conservation measures onto farmers’ fields must have contributed to some extent to the nation’s success in controlling erosion-induced losses of soil productivity. The point here is the success of the effort, which owes something to SCS programs, something to farmers’ own interest in protecting the productivity of their land wherever it is threatened, and something also to the likelihood that the threat never was as severe as was commonly believed.
the United States do not exist for any other country. We here discuss data and a number of studies found in a non-exhaustive search of the literature. We are satisfied, however, that an exhaustive search would not materially change the conclusions arrived at here.

Bronger and Bruhn (1988) say that "red soils" (mainly Alfisols) cover about 700,000 km² in India, or 40 percent of the agricultural land in the country. The depth of these soils is less than 1 m in most areas. Although studies of erosion across this whole area have not been done, experimental work at ICRISAT is suggestive. This work was undertaken in 1975-83 to measure erosion in the Hyderabad area using the traditional cultivation system to produce sorghum and pigeonpeas. The results showed erosion from the site of 3.6 t/ha/y. This would remove 2.5 cm of topsoil in 100 years (Bronger and Bruhn 1988, p. 688), about one-third of the amount the U.S. Soil Conservation Service believes to be the maximum consistent with long-term maintenance of soil productivity. However, the per hectare amount of soil erosion is a poor indicator of the productivity effect in the absence of knowledge of the relationship of erosion to yield-sensitive characteristics of the soil. The yield effect of a given amount of erosion on the Alfisols of India may be more or less than the effect of that amount on the soils of, e.g., the midwestern United States. Indeed, Stocking (1984) asserts that the major groups of soils common in tropical areas (of which Alfisols are one) are more susceptible to erosion and productivity decline than temperate-zone soils.

Lal (1984) takes the same position. He notes that, on most tropical soils, organic matter is of critical importance in determining soil fertility and is more concentrated in the upper part of the soil profile than in temperate zone soils. Consequently a given amount of erosion on a tropical soil is likely to remove more organic matter and soil nutrient, and thus affect productivity more strongly, than the same amount on a temperate zone soil.

In experimental work in Nigeria, Lal (1984) got mixed results in testing the yield response to fertilizer after removal of topsoil. No fertilizer combinations compensated for the loss of maize and cowpea yields when the topsoil was removed from a Vertisol in southeast Nigeria. (Vertisols are another major tropical soil). However, Lal found that, on two Alfisols in the southwestern part of the country, combinations of 60 and 120 kg/ha of nitrogen fertilizer with 15 and 30 kg/ha of phosphorus gave grain yields on plots where 5 cm of topsoil had been removed which were comparable to yields on uneroded control plots. An erosion rate of 11 t/ha/y, the SCS standard, would remove 5 cm from a hectare of land in about 60 years. The erosion rate reported by Bronger and Bruhn for Indian Alfisols would remove 5 cm of topsoil from a hectare in about 200 years.

A study by Bishop and Allen (1989) of the economic costs of erosion-induced productivity losses in Mali is an ambitious, even bold, undertaking that yields useful results and insights. The study is bold because it uses a slim database to estimate the economic costs of erosion-induced productivity losses for Mali as a whole. It is useful because it is carefully done and provides "ballpark" estimates of the scale of the erosion problem in Mali. More importantly, the study highlights the kinds of data and
analytical techniques needed to undertake such studies, and thus could stimulate efforts to develop these materials further, not only in Mali but in other countries as well.

Briefly, Bishop and Allen (1989) used the Universal Soil Loss Equation (developed in the United States but here adapted to west African conditions) to estimate cropland erosion in an area of Mali comprising about one-third of the nation's most productive cultivated land. They then used regression models of the erosion-yield loss relationships developed at the International Institute for Tropical Agriculture (IITA) in Nigeria to estimate the impact of erosion on crop yields in Mali over a 10-year period. Crop and input prices were used to value the net loss of crop output per hectare per year over the 10 years. The losses were assumed to be cumulative, i.e., the second-year loss equals the loss that year plus the first-year loss, and so on for the subsequent years. The annual stream of 10-year losses was discounted and summed to get the present value of the per hectare cumulative loss. This estimate was multiplied by the number of hectares in the crops studied in the country as a whole to get a nationwide estimate of the losses. Under the most conservative assumptions about the productivity impacts of erosion, the estimated losses were 1.5 percent of Mali's Gross Domestic Product (GDP) and 4 percent of its Gross Agricultural Product (GAP).

Bishop and Allen are careful to point out that these results do not indicate that Mali could increase its GDP or GAP by 1.5 percent or 4 percent, respectively, by eliminating the productivity effects of erosion. The reason is that eliminating the effects would cost something. To address the question of how much Mali's income might be increased by controlling erosion, Bishop and Allen compared the costs of various erosion control practices in Mali with the costs of erosion-induced productivity losses. They concluded that

"...economic losses due to soil erosion in Mali are probably high enough, in certain areas, to justify moderate investment in farm-level soil conservation, under even relatively conservative assumptions. ...Under more extreme assumptions about the impact of erosion on crop yields and more favorable assumptions about the cost of soil conservation..." erosion control over a wider area likely would be economical (Bishop and Allen 1989, p.29).

Bishop and Allen hedge this conclusion in various ways, noting especially the fragility of the underlying data and the hazards of extrapolating relationships across different areas, e.g., from experimental work at the IITA in Nigeria to farmers' fields in Mali, and from those fields to much of the agricultural land in the country. The authors nonetheless believe that their results are at least of the right order of magnitude, and we have no reason to question that judgment.

A by-product of the Bishop/Allen study is its showing that the calculated yield losses in Mali occur even though the annual rate of erosion is only 6.5 t/ha/y. On most soils in the United States, such a low rate of soil loss almost surely would have no measurable effect on crop yields, even over a very long period. The Bishop/Allen
finding, therefore, appears consistent with the arguments of Stocking (1984) and Lal
(1984), noted above, that tropical soils are more sensitive to erosion than temperate-
zone soils.

Other observations on erosion and soil productivity in LDCs. A couple of further
observations are worth making in seeking a perspective on the erosion problem. One
concerns the importance of guarding against the interpretation of soil-erosion estimates
as indicators of the amount of soil forever lost to agricultural production. Erosion
estimates are measures of the amount of soil moved from one place to another. The
Universal Soil Loss Equation measures the amount of soil moved from a point on the
landscape to another point where it either is deposited or enters a stream. The Wind
Erosion Equation developed in the Great Plains of the United States measures the
amount of soil picked up from one place on the earth's surface and deposited at some
other place.

Many studies show that most of the soil eroded from the landscape in any year
is stored somewhere else on the landscape for years, decades or even centuries before
it is delivered to the oceans. In a study of the southern Piedmont in the United States,
Trimble (1975) found that, by the early 1970s, only about 5 percent of the soil eroded
over the previous two centuries had been delivered to the fall line of the rivers in the
region. In a similar study of the Coon Creek basin in Wisconsin, Trimble (1981) and
Trimble and Lund (1983) found that, in the 122 years from 1853 to 1975, only 6 to
7 percent of the soil eroded from upland areas and valleys tributary to Coon Creek was
exported from the basin to the Mississippi River. Trimble does not consider the fate
of the soil delivered to the Mississippi, but his work on the Piedmont (and that of
others in the United States, e.g., Meade and Parker 1985) indicates that much of it
would be stored on flood plains and other parts of the Mississippi basin before it was
finally delivered to the Gulf of Mexico.

The U.S. situation with respect to the movement and storage of eroded soil is
replicated around the world, although the details, of course, vary. Mahmood, for
example, in a study of reservoir sedimentation in many countries cited Trimble's Coon
Creek study as being relevant in characterizing sediment movement in watersheds
upstream from reservoirs (Mahmood 1987).

Much of the soil moved by erosion is deposited in non-farmable places, e.g.,
riverbeds, forests, gullies, but much of it also remains available for agricultural use.
For example, Larson, Pierce and Dowdy (1983) presented data for five watersheds in
Minnesota varying in size from 1100 to 3300 km², which indicate that only 0.8 to
26.9 percent of the soil eroded in the watersheds entered stream channels. The rest
was deposited on cropland, pasture, forestland or wasteland. Much of what eroded
from cropland probably was deposited on other cropland.

Seckler (1987) points out that the rich alluvial plains, where much of the
world's food supply is produced, were built by geological erosion. More to the present
point, he states (p.85) that "...a good part of the agricultural land in mountainous areas
of Asia has been created by sediment traps and sediment deposition through irrigation,
sometimes abetted by deliberate destruction of groundcover in the watershed to
accelerate natural rates of erosion." And in a study of the productivity effects of soil erosion in Java, Magrath and Arens (1989) did not include a region with 37 percent of the land area of the island (not counting wetlands) because the region suffers little erosion "... and in fact benefits from the deposition of nutrients from erosion upstream..." (Magrath and Arens 1989, p.17).

Clearly, not all soil moved by erosion is lost to future agricultural production. This must be kept in mind when interpreting studies of the effect of erosion on soil productivity. Losses at one site on the landscape may be partially compensated by gains somewhere else. (The three models of erosion-productivity relationships, discussed above for the United States, do not take account of possible compensating effects of soil deposition.)

Research done in the United States indicates that, where erosion significantly reduces soil water-holding capacity, fertilizer applied to restore soil nutrients will not generally compensate for the loss of yields. Research in LDCs (e.g., Deuson and Sanders 1988; Pingali 1989) suggests the same conclusion.

Loss of soil water-holding capacity thus appears to be a particularly serious consequence of erosion because increased use of fertilizer cannot compensate for the resulting yield loss. It may follow that farmers whose land had suffered erosion-induced losses of soil water-holding capacity may not seek to compensate by applying more fertilizer because the yield response may be inadequate to cover the increased cost.

This line of reasoning suggests to Crosson (Crosson 1987, p.184) but not to Anderson that it may be possible to glean some hints about the severity of the erosion problem in LDCs by examining their rates of use of fertilizer. If the line of reasoning is correct, then the more rapid the increases in fertilizer use, the less reason there could be to believe that erosion had impaired soil water-holding capacity.

Table 3.8 shows fertilizer use per hectare in Africa, Latin America and Asia, and for selected countries in each region. Between 1975/77 and 1985/87, per hectare use increased in each major region: 36 percent in Africa, 39 percent in South America and 121 percent in Asia. Among the 49 African countries listed in the source, use per hectare increased in 31, remained the same in 11 and declined in 7. The largest declines were in the three countries shown.

The selection of countries shown in Table 3.8 was based roughly on a combination of size and evidence that erosion may be a problem. Kenya, for example, is often cited as a high-erosion country. In South America, Brazil is shown because of its size, and Colombia, Ecuador and Peru because, as Andean countries, their erosion rates generally are believed to be high. The Asian countries were selected because they are large (except Nepal) and all are often cited as having significant erosion problems.

We must not read too much significance about erosion-induced productivity losses from Table 3.8. There are too many factors influencing fertilizer rates in a
Table 3.8: Average Annual Fertilizer Rates in Less-Developed Countries
1975/77 and 1985/87

<table>
<thead>
<tr>
<th></th>
<th>Rate</th>
<th>Rate</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1975/77</td>
<td>1985/87</td>
<td>(%)</td>
</tr>
<tr>
<td>AFRICA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Selected countries with increasing use</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kenya</td>
<td>22</td>
<td>46</td>
<td>109</td>
</tr>
<tr>
<td>Nigeria</td>
<td>2</td>
<td>10</td>
<td>400</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>48</td>
<td>56</td>
<td>17</td>
</tr>
<tr>
<td>Selected countries with decreasing use</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Côte d'Ivoire</td>
<td>14</td>
<td>9</td>
<td>-36</td>
</tr>
<tr>
<td>Ghana</td>
<td>10</td>
<td>4</td>
<td>-60</td>
</tr>
<tr>
<td>Liberia</td>
<td>16</td>
<td>5</td>
<td>-67</td>
</tr>
<tr>
<td>SOUTH AMERICA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Selected countries</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brazil</td>
<td>41</td>
<td>49</td>
<td>20</td>
</tr>
<tr>
<td>Colombia</td>
<td>49</td>
<td>81</td>
<td>65</td>
</tr>
<tr>
<td>Ecuador</td>
<td>26</td>
<td>34</td>
<td>31</td>
</tr>
<tr>
<td>Peru</td>
<td>38</td>
<td>43</td>
<td>13</td>
</tr>
<tr>
<td>ASIA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Selected countries</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>China</td>
<td>74</td>
<td>195</td>
<td>164</td>
</tr>
<tr>
<td>India</td>
<td>22</td>
<td>52</td>
<td>136</td>
</tr>
<tr>
<td>Indonesia</td>
<td>27</td>
<td>100</td>
<td>270</td>
</tr>
<tr>
<td>Nepal</td>
<td>6</td>
<td>20</td>
<td>233</td>
</tr>
<tr>
<td>Philippines</td>
<td>34</td>
<td>50</td>
<td>47</td>
</tr>
<tr>
<td>Thailand</td>
<td>14</td>
<td>26</td>
<td>86</td>
</tr>
</tbody>
</table>


Note: Among the 12 South American countries listed in the source, use declined only in Uruguay (from 43 to 41 kg/ha). Per hectare use increased in all of the 37 Asian countries listed in the source.
country that have nothing to do with erosion. Much of the increases in India and China, for example, were on irrigated land with little inherent erosion potential. The increases would thus be consistent with large erosion-induced losses of productivity on rainfed land. Irrigation is much less important in the other four Asian countries, however, each of which had high increases in fertilizer intensity and is often cited as having high erosion. Here too, however, caution is needed in interpreting the table results, at least for Indonesia. Magrath and Arens (1989) estimate very high erosion-induced productivity losses in the uplands of Java, which do not show up in actual yields -- they have been increasing by 3-4 percent per year -- because the estimated losses were offset by the massive increases in fertilizer use. Much of the fertilizer increase, according to Magrath and Arens, is due to a substantial government subsidy. Despite these several caveats, one interpretation is that the data in Table 3.8 are consistent with the hypothesis that, whatever the effects of erosion on soil productivity in the LDCs may be, they have not so far seriously impaired soil water-holding capacity.

**Other consequences of soil degradation.** The discussion here of the effects of soil degradation on land supply has dealt with the effects of degradation on the productivity of land which remains in agricultural production. But on some marginal land, degradation may result in the land going entirely out of agricultural production, another instance of the mix of land quality and land quantity in determining land supply. We have no way of estimating the amount of land which may be withdrawn from agriculture because of degradation, but it could be significant in some of the arid and semi-arid parts of the LDCs.

**Summary on the Extent of Land Degradation**

Apart from the U.S., the information about land degradation and its consequences is skimpy and anecdotal. As far as it goes, the information suggests that land degradation is serious in some parts of some countries. If the situation analyzed by Bishop and Allen (1989) in Mali is replicated in other areas -- and there is every reason to believe that it is -- then the productivity consequences of land degradation in some parts of such areas are serious enough to justify intervention to bring them under control. Other studies reviewed, however, suggest that many areas apparently seriously affected by land degradation show a resiliency, a capacity to recover with more favorable weather, that is greater than is generally believed.

Soil erosion has been given special attention as a form of land degradation in LDCs, and properly so in our judgment (Anderson and Thampapillai 1990). Information about erosion and its consequences is only slightly less skimpy than information about other forms of degradation. Our review of the information supports a few general conclusions:
(a) The yield effects of given amounts of erosion are likely to be greater on tropical soils than on temperate-zone soils.

(b) As in the temperate zone, fertilizer can compensate for part or all of erosion-induced losses of yield on some tropical soils, and not on others.

(c) Judgments about the severity of erosion-induced losses of soil productivity must take account of possible compensating gains in areas of deposition.

Summary on the Potential Supply of Land

The supply of land has both quantitative and qualitative dimensions. Estimates of the quantity of potential additional cropland globally indicate that the amount is about the same as land now in crop production. This estimate greatly overstates the potential supply of cropland, however, both because most of the land is in Africa and Latin America while much of the increased demand for crops will be in Asia, and because the estimates do not take account of the environmental and economic costs, including opportunity costs, of converting the land from forest, range and pasture to crops.

The potential cropland also is of generally inferior quality than land now in crops. But the qualitative dimension is relevant not just to potential cropland but also to land now in production. Although there now is great concern about perceived rates of degradation of this land, there is very little good information about the rates (Anderson and Thampapillai 1990), except with respect to soil erosion in the United States. Most studies show that in that country, erosion is not a serious threat to the long-term productivity of the land.

We expect the economic and environmental costs of bringing more land under crops will prove more limiting to expansion of the supply of land than losses of productivity because of land degradation. In any event, it appears virtually certain that the potential supply of additional cropland is substantially less than the current supply of such land.
CHAPTER 4
THE WATER RESOURCE

Introduction

The supply of water to agriculture comes almost exclusively from precipitation, directly in the case of rainfed production and indirectly in irrigated production. In this chapter we assume no long-term changes in climate, so the supply of precipitation to agriculture around the world is assumed to be fixed, i.e., that precipitation and temperature means and variances remain as they now are. In this case, precipitation will contribute nothing directly to increasing the supply of water available for agriculture over the period of the demand scenario. Thus, if the global supply of water to agriculture is increased over that period, it will come primarily through expanding the presently irrigated area. This chapter considers the potential for doing that. As in the case of the land resource, we consider the potential expansion of irrigation within the existing knowledge regime.

Potential for Increased Irrigation

In 1986, global irrigated land was 253 million ha, 2.5 times more than in 1950 (World Bank/UNDP 1990). Almost two-thirds of this was in five countries: India (56 million ha), China (46 million ha), the United States (23 million ha), the Soviet Union (21 million ha) and Pakistan (16 million ha). Of the 253 million ha, 185 million (73 percent) were in the LDCs. India, China and Pakistan alone accounted for 118 million ha, 47 percent of the world total and 64 percent of the LDC total. The next three most important LDCs in irrigated hectares were Indonesia (7.3 million), Iran (5.8 million) and Mexico (5.3 million). Table 4.1 gives the hectarage of irrigated land by the three less-developed regions of the world. The dominance of India, China and Pakistan is apparent.

The 253 million ha of irrigated land was 17 percent of global cropland, but it accounted for more than one-third of total world food production. In the less-developed world, almost 60 percent of rice and 40 percent of wheat production -- by far the major crops -- is on irrigated land (World Bank/UNDP 1990, p.3). The FAO estimates that, from the mid-1960s to the mid-1980s, the expansion of irrigation accounted for over one-half the increase in global food production (cited by World Bank/UNDP 1990, p. 103).

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1There is some variation in estimates of global irrigated land. Stewart, Lal and El-Swaify (1991) estimate 94 million ha in 1950 and 271 million in 1985. Yudelman and Hillel (1988) state that, from the mid-1950s to the mid-1980s, the amount of irrigated land grew from around 140 million ha to close to 300 million. Rosegrant (1991), citing FAO estimates, gives a figure of 224 million ha in 1988. In the absence of evidence that other estimates are better, we use those of the World Bank/UNDP.
Table 4.1: Irrigated Land in the Less-Developed Countries in 1986

<table>
<thead>
<tr>
<th>Area</th>
<th>Share of LDC total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(thousand ha)</td>
<td>(%)</td>
</tr>
<tr>
<td>AFRICA</td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>7,560</td>
</tr>
<tr>
<td>Sub-Saharan</td>
<td>3,465</td>
</tr>
<tr>
<td>LATIN AMERICA</td>
<td></td>
</tr>
<tr>
<td>North and Central</td>
<td>7,035</td>
</tr>
<tr>
<td>South</td>
<td>9,200</td>
</tr>
<tr>
<td>ASIA</td>
<td></td>
</tr>
<tr>
<td>Far East</td>
<td>140,065</td>
</tr>
<tr>
<td>Near East</td>
<td>18,315</td>
</tr>
</tbody>
</table>


The past and present importance of irrigation in world agricultural production, especially in Asia, is apparent. But how much potential is there for continued expansion of irrigated land over the next several decades? The World Bank/UNDP (1990) estimates that there is an additional 137 million ha worldwide which has potential for irrigation, although noting that the estimate is speculative because it depends not only on the physical resource base but also on future economic conditions.

Table 4.2 shows the estimates of remaining land with potential for irrigation. Globally, 137.5 million ha of potentially irrigable land remains, 80 percent of it in the LDCs. Although the greatest potential percentage increases are in South America and Sub-Saharan Africa (217 percent and 477 percent, respectively), the greatest absolute potential is in the Far East, with 69.4 million ha. This is 58 percent of the total potential increase in LDCs. Almost 60 percent of the LDC potential is in just three countries: Brazil, China and India (World Bank/UNDP 1990, p. 104). India and China plan to develop virtually all of their remaining potential by 2000 (World Bank/UNDP 1990, p. 104).
Table 4.2: Presently Irrigated Land and Land with Irrigation Potential

<table>
<thead>
<tr>
<th></th>
<th>Presently irrigated (thousand ha)</th>
<th>Potentially irrigable (percent)</th>
<th>Potential increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>More-developed countries</td>
<td>68,000</td>
<td>27,000</td>
<td>40</td>
</tr>
<tr>
<td>Less-developed countries</td>
<td>186,000</td>
<td>110,500</td>
<td>59</td>
</tr>
<tr>
<td>Global</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Africa</td>
<td>11,025</td>
<td>18,175</td>
<td>165</td>
</tr>
<tr>
<td>North</td>
<td>7,560</td>
<td>1,640</td>
<td>22</td>
</tr>
<tr>
<td>Sub-Saharan*</td>
<td>3,465</td>
<td>16,535</td>
<td>477</td>
</tr>
<tr>
<td>Latin America</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North and Central</td>
<td>16,235</td>
<td>22,865</td>
<td>141</td>
</tr>
<tr>
<td>South</td>
<td>7,035</td>
<td>2,865</td>
<td>41</td>
</tr>
<tr>
<td>9,200</td>
<td></td>
<td>20,000</td>
<td>217</td>
</tr>
<tr>
<td>Asia</td>
<td>158,380</td>
<td>69,420</td>
<td>44</td>
</tr>
<tr>
<td>Near East</td>
<td>18,315</td>
<td>5,185</td>
<td>28</td>
</tr>
<tr>
<td>Far East</td>
<td>140,065</td>
<td>64,235</td>
<td>46</td>
</tr>
</tbody>
</table>


* Olivares (1990) estimates that Sub-Saharan Africa now irrigates about 5 million ha, with another 15 million ha potentially irrigable land. His total, 20 million ha, thus agrees with that in this table.

Constraints on Realizing Potential

These estimates of potentially irrigable land must be treated with the same caution as those for potential cropland discussed in Chapter 3. The World Bank/UNDP report (1990, p. 103) notes that the potential for expanding both rainfed and irrigated cropland is "becoming increasingly constrained by resource limitations," especially in Asia and North Africa. The report notes further that, in the 1970s, the rate of increase in irrigated area was only about half the 1960s rate. The slower growth is attributed in part to the decline in grain prices in the late 1970s and to the growing constraint on resources (World Bank/UNDP, p. 104). Stewart, Lal and El-Swaify (1991, p.125) also show a declining rate of expansion in global irrigated land since the 1960s, although the rate of decline is not as sharp as indicated by World Bank/UNDP. The Stewart, Lal and El-Swaify numbers are shown in Table 4.3.
Table 4.3: Estimates of Global Irrigated Land, 1950-1985

<table>
<thead>
<tr>
<th>Year</th>
<th>Area (million ha)</th>
<th>Average Annual Change (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>1960</td>
<td>140</td>
<td>4.1</td>
</tr>
<tr>
<td>1970</td>
<td>198</td>
<td>3.5</td>
</tr>
<tr>
<td>1985</td>
<td>271</td>
<td>2.1</td>
</tr>
</tbody>
</table>


What are these constraints, and how might they affect the expansion of irrigation over the next several decades. We address the question primarily with respect to the LDCs, but give some attention also to the USA.

Some of the constraints on future expansion of irrigation are implicit in the performance of the present system. The World Bank/UNDP report (1990) asserts that "...more than half the irrigated area in the world today is in need of rehabilitation or modernization." In a study of irrigation performance and potential in India, the World Bank (1991a, p. 63) asserted that "Field observations suggest that all states in India suffer in various degrees from inadequate maintenance expenditures" for irrigation. The report goes on to say that there were substantial increases in spending on irrigation in India in the early 1980s but most of it went for increased staff and had little productive impact.

The World Bank/UNDP (1990) reported a general perception that irrigation systems in the LDCs operate well below design capacity. In many places the area actually irrigated is less than the command area, and cropping intensities (the number of crops taken per hectare per year) are less than expected. Much water is wasted in transmission losses, and because of "inadequate, unreliable and untimely water deliveries" (World Bank/UNDP 1990, p.19). In addition, much of the construction work on irrigation systems is shoddy, projects frequently are left unfinished, and monitoring of salinity build-up and waterlogging of the soil is deficient. Another World Bank report (1991b) expresses the same views with respect to irrigation in India.

Some of these deficiencies may reflect budgetary constraints on irrigation agencies around the world, but much apparently is due also to poor management. Indeed, the FAO position (as reported in World Bank/UNDP 1990) is that the problems of irrigation performance in most LDCs are largely managerial. The World Bank/UNDP report (1990, p. 25) also takes the position that management deficiencies are a major constraint on performance of these systems, and adds "related institutional
problems" as another constraint as well as in some cases technical deficiencies that may be amenable to new technological research. Among these institutional problems, the report notes particularly a lack of contact between the managers of irrigation systems and the farmers using the water.

In India, poor management is cited as one of the reasons for rising irrigation investment costs (World Bank 1991a). From the Fifth Plan in 1974-79 to the Sixth Plan (1980-85) investment costs per hectare rose 57 percent in real terms. Although the reasons for this are not entirely clear, the World Bank (1991b p. 62) suspects an important cause was "implementation inefficiencies because of lax contracting and supervision practices in the presence of inadequate systems for monitoring, cost analysis and control of expenditures."

Rosegrant (1991) cites studies showing that, as well as in India, rising real costs per hectare were among the most important causes of declines in the 1980s of irrigation investments in Indonesia, the Philippines, Sri Lanka and Thailand. A decline in rice prices was the other main cause.

Poor management often is cited as the reason why in many surface irrigation systems water use efficiency (WUE) -- the percentage of water available which is actually applied to farmers’ fields -- is low. Rosegrant (1991) asserts that, in Asia, WUE in many, perhaps most, such systems varies between 25 and 40 percent. From such appraisals, several observers have concluded that improvements in WUE could significantly expand the irrigated area, or increase crop yields, or both without major new investments.

Rosegrant (1991), however, casts some doubt on the potential of improvements in WUE as a source of higher irrigated production. He notes that the low estimates of WUE typically are for individual irrigation systems rather than for a collection of linked systems in which water is used and re-used as it moves downstream from one system to the next. When account is taken of re-use, WUE on a basin-wide scale can be substantially higher than it is for individual systems. As an example, Rosegrant cites Egypt where WUEs for individual components of the Nile system are as low as 30 percent but for the system as a whole, WUE is about 70 percent.

In the studies reviewed here, the statements about poor irrigation management apply almost exclusively to governmentally financed, constructed and managed surface water systems. However, at present, much irrigation water is provided by privately financed tubewells. In India, where this form of irrigation probably is most developed, 21 million of the nation’s 43 million ha of net irrigated area (49 percent) was watered by tubewells in 1986/87, almost all of them privately financed. Moreover, from 1967/68 to 1986/87, 76 percent of the addition to net irrigated area in India was from this source (Rosegrant 1991, p. 53). Tubewell development was also of major importance in the expansion of irrigation in Pakistan and Bangladesh in this period.

Tubewell development has occurred most rapidly in areas relatively well served by roads, research and extension facilities, credit institutions, and with a dependable supply of energy for pumping and distributing water (Rosegrant 1991). These usually are areas with large public surplus water systems. Percolation of water
from these systems replenishes groundwater supplies, and proximity to the systems provides farmers opportunities for conjunctive management of ground and surface waters in watering their fields (Rosegrant 1991).

Some observers have expressed concern that only more wealthy farmers can afford to invest in tubewells, an argument against tubewells on equity grounds. Rosegrant (1991), however, citing studies in India and Pakistan, asserts that in fact "inequalities in rural income in areas of high tubewell penetration are dwindling and benefits emanating from new technology are widely shared with small and medium farmers" (p. 39). The reason is that competition among tubewell owners to provide water to other farmers has resulted in well-developed markets for the resource. This has inhibited collusive behavior among tubewell owners and provided access to water by farmers too poor to invest in their own wells. Rosegrant (1991, p. 39) concludes that these conditions of tubewell expansion are attractive on both efficiency and equity grounds.

Prices for irrigation water, where it is priced at all, generally are well under the marginal social value of the resource. The resulting rates of use, although appreciated by farmers, are socially excessive. These pricing policies pose a constraint on the expansion of irrigation in the sense that, with more efficient pricing, more land could be irrigated with a given amount of water.

Curiously, neither the World Bank/UNDP (1990) nor the two World Bank volumes dealing with irrigation in India (1991a, 1991b) place much emphasis on water pricing policies as a source of inefficient use of water by farmers. In the case of the World Bank (1991a) report, the reason is that moving to efficiency pricing of water in India would face serious limitations, given the physical characteristics of some of the irrigation systems. Nevertheless, the Bank argues that water charges generally are low relative to the marginal value of the water to farmers and higher charges would ease some of the burden of financing the system. By implication, a system of higher charges would make it easier also to finance the costs of expanding the system. What is true of India in this case should be true also for publicly funded systems all around the world.

Managerial and financial inefficiencies clearly are important constraints to realizing the potential for irrigation in India and elsewhere, but there are others. Although the World Bank/UNDP report endorses the FAO estimate that Sub-Saharan Africa has the potential to increase irrigated land to roughly 20 million ha (see Table 4.2), the report also notes several constraints to achieving the potential. There are relatively few major rivers in Sub-Saharan Africa and the flows are strongly seasonal, particularly in the Senegal and Niger rivers. Typically many of the smaller rivers carry no water at all during the dry season. Opportunities for damming rivers are limited and over much of the region water yields from wells are small. The principal potential source of groundwater is in alluvial river beds and flood plains.

Apart from these natural constraints to further irrigation development in Sub-Saharan Africa, there are others. The general lack of infrastructure -- the sheer difficulty of moving equipment and material around -- has tended to increase irrigation development costs relative to other regions. And a recent study by the FAO concluded that one of the major constraints to further development and operation of irrigation
systems in the region was the lack of properly-trained people (World Bank/UNDP 1990).

The World Bank (1991a) report on irrigation in India makes a related point about that country. In eastern India, socioeconomic factors constrain the present performance of irrigation systems; by implication they also would constrain future expansion. By contrast with some northwestern states, such as Punjab, farms in eastern India are small and fragmented, and often are operating under sharecropping or other tenancy systems that may discourage efficient use of water. Crop yields are relatively low, most people are very poor, and infrastructure and other government services are weak. This complex of socioeconomic conditions inhibits more efficient use of the region’s irrigation systems and likely would also impede expansion of the system.

It also should be noted that the estimates of potentially irrigable land in the LDCs give greater weight to soil and climatic conditions than to market conditions in determining irrigability. If the soil and climate factors would permit some crop to be grown under irrigation, the land is considered to be potentially irrigable. But if the crops favored by climate and soils have little market potential, farmers will have weak incentives to invest in irrigation, regardless of the favorable soils and climate. Economic conditions are not the sole determinants of irrigability, but they probably deserve more weight than they get in current estimates of potentially irrigable land in LDCs.

None of the materials reviewed for this paper has much to say about increasing demands for non-agricultural uses of water as a constraint on expanded irrigation. This may be of major importance in some areas. Projections of urban populations in LDCs given in Chapter 3, Table 3.7, indicated an almost doubling from 1990 to 2010 and tripling from 1990-2025. Urban population in Africa would increase by almost 700 million -- more than four-fold -- in South Asia by 1 billion -- a tripling -- and in East Asia (ex Japan) by 450 million -- two- and one-half times. These enormous increases in urban populations would generate comparably large increases in demand for water. To be sure, in most countries where irrigation is significant, some 80 to 90 percent of water consumption is in agriculture, so a relatively small percentage diversion from irrigation could supply a large percentage increase in urban demands. The issue here, however, is not the diversion of present supplies of water from agriculture to urban uses but the competitive position of agriculture in bidding for large additional supplies in the face of explosive growth in demand for urban uses.

In the MDCs, and in some LDCs, irrigation also is confronting increased competition for water to maintain or enhance environmental values. In the United States, this source of demand for water already is strong, and a major competitor with agriculture for water in the arid and semi-arid regions of the country (Frederick 1991). The combination of increasing population, particularly urban population, and per capita income in LDCs seems sure to stimulate rising demand also for water-based environmental services. By the second or third decade of the next century, this

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2A calculation by William Magrath, ASTAG, World Bank, indicates that, at present rates of water use per hectare in agriculture and per urban person in less-developed countries, the projected increase in urban population in those countries could be accommodated by the water now used to irrigate 30,000 to 50,000 ha.
environmental services. By the second or third decade of the next century, this demand could be a powerful competitor with agriculture for water, thus constraining the further expansion of irrigation.

Finally, salinization and waterlogging may constrain future gains in production from irrigated land. The growth of irrigation over the past 40 years in the LDCs has resulted in the spread of such water-related diseases as malaria, onchoceriasis (river blindness), and schistosomiasis (bilharzia) (Jensen, Rangeley and Dieleman 1990). The building of large dams for irrigation has also disrupted ecosystems upstream from the dam because of reservoir flooding and downstream by disruption in the flows of river water. Rising concern about these human health and environmental impacts of large irrigation systems also could constrain their further expansion. Two processes cause salinization of irrigated land. One, probably the most important, is the upward movement of salts with capillary rise from shallow groundwater, the evaporation of the water and deposition of salts on the soil surface. Salinization occurs also because the water farmers use for irrigation tends to pick up salts from the land irrigated, so that the salt concentration of the water leaving a farmer’s field in irrigation return flow tends to be higher than when the water was applied. As the water moves downstream, being used and reused by successive farmers, the salt content continues to rise, and to increase the salt content of the soil irrigated by the water. In time, the increased salinization of the soil depresses crop yields. In addition, some of the more saline irrigation water applied may percolate to the groundwater, increasing its salt content. When this water is subsequently pumped and used for irrigation, it too can cause a build-up of salt in the soil.

Waterlogging of the soil may also adversely affect yields on irrigated land. But waterlogging is not limited to irrigated land. It can occur on any land that is inadequately drained. Where such land is irrigated, waterlogging raises the soil-water table with successive irrigations. Too much water in the soil can depress yields just as can too much salt.

Proper drainage is the answer to waterlogging; use of enough irrigation water to flush salts from the soil, combined with proper drainage, is the prescribed method for reducing soil salinity. The techniques for doing these things are well understood, but often they are not applied. The World Bank/UNDP (1990) report states that in India, China, and Pakistan -- where the percentages of arable land irrigated are 33, 48 and 77, respectively -- waterlogging and salinity are major problems. (As noted above, India and China, in that order, lead the world in irrigated area, with Pakistan in fifth place.)

The report by the Bank’s India Department, however, (World Bank 1991b, p.72) raises a question about how ”major” the salinization/ waterlogging problem is on India’s irrigated land. The report indicates that, on average, waterlogging and/or salinization affects some three percent of the country’s irrigation command area - an extent that some observers regard as an unbelievably low estimate. For the most part, the problems are localized, but they are of increasing concern in the northwest, particularly in large parts of the states of Punjab and Haryana, but also in Rajasthan and Gujarat.

The World Bank’s India Department (1991b) attributes the lack of attention to drainage in Indian irrigation projects to the fact that the payoff to
investments in drainage is long-term -- salinity and waterlogging problems arise only after some years of irrigation -- relative to the payoff to investments in expanding the irrigated area. This reason probably goes far to account for the relative lack of attention to drainage in much of the world’s irrigated area.

On a global scale, what can be said about the effects of salinization and waterlogging on crop yields? The data do not permit precise answers. Postel (1989) estimates that roughly 25 percent of the world’s irrigated land is “affected” to a greater or lesser extent by salinity and waterlogging. This means that yields on this land are less than they would be in the absence of these conditions, but Postel provides no estimates of the yield loss. Moreover, Postel’s estimate that 25 percent of global irrigated land is affected by salinity and waterlogging implies that the percentage of such land affected in countries other than India is of an order of magnitude greater than the percentage in India.\(^3\) This clearly is not the case in the United States (Frederick 1991) with almost 10 percent of global irrigated land. There is no reason in principle why the percentage of irrigated area affected by salinity and waterlogging in China, the CIS republics, Pakistan, and other countries could not be ten times the percentage in India. But the difference is so large that, on its face, it suggests either that Postel’s global estimate of 25 percent is too high or that the India Department’s three percent estimate is too low. This is an issue needing further investigation.

Because salinity and waterlogging build up over time, they may represent an increasing threat to yields on presently irrigated land which could offset some of the production increases obtained by expanding the irrigated area. In this respect, the productivity effects of salinity and waterlogging are like those of soil erosion on the productivity of the land. How important the salinity and waterlogging constraints prove to be will depend in large measure on the ability of the LDCs with substantial irrigation investments to improve irrigation management.

Conclusion

Although present estimates suggest rather considerable potential for additional irrigation in both the MDCs and LDCs, much of this might prove illusory, given the present knowledge about irrigation. Realization of the potential confronts several serious constraints. The economic costs of additional irrigation have been rising, and are expected to continue to rise, reflecting both deeply ingrained managerial inefficiencies in publicly-built and operated systems and the fact that the most favorable sites have already been developed. Moreover, competition from urban and environmental users of water is expected to increase sharply in all countries.

Reducing management inefficiencies would help to extend the supply of irrigation water but the potential here may also be less than it appears for a couple of reasons. One is that the basin-wide efficiency of water use often is much higher than

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\(^3\)India’s 56 million ha of irrigated land (see above) is 22 percent of the world total. If three percent of the Indian land is affected by salinity and waterlogging (India Department, July 3, 1991) and 25 percent of the world total is so affected (Postel 1989), then 30 percent of the irrigated land in countries other than India is affected.
the efficiency of use in individual irrigation projects. Measures of project inefficiency, therefore, likely overstate the potential increases in supply from more efficient use. The second reason is that, at least in South Asia, a substantial proportion -- 50 percent in India -- of the irrigated area is irrigated from private tubewells. Farmers who have invested in these systems have strong incentives to manage efficiently, and research in India and Pakistan indicates that, in fact, they are so managed. Consequently, the potential for expanding the supply of irrigation water by more efficient management of these systems must be small.

On balance, while our analysis has been heavily influenced by better documented Asian experience, it appears unlikely that global supplies of irrigation water, within the existing knowledge regime, can be expanded enough to accommodate more than a small part of the increased demand for food represented in the demand scenario.
CHAPTER 5

THE GENETIC RESOURCE

Introduction

Crops and animals are under continuing assault from a host of pests and diseases, and from the vicissitudes of often harsh climates. Maintenance of present levels of crop and animal production requires a sustained effort by plant and animal breeders to develop new varieties better able to resist the relentless attacks. Expanding production on the scale indicated in the demand scenario will require an even more intensive effort by breeders, as is taken up in Chapter 9.

The challenge, however, is not limited to simply increasing the potential long-term average yield of crop varieties. There is evidence that the trend toward monoculture around the world has increased the vulnerability of crop production to extremes of weather fluctuations and to outbreaks of insect or disease attacks. Use of the plant genetic resource to counter these inter-annual threats to production will be increasingly important.

Similarly, it will be necessary to pay more attention than in the past to the specifics of climates and soils around the world in designing crop breeding programs. This too will increase the potential value of maintaining and enhancing the crop genetic resource.

To be successful in this challenging undertaking, breeders must have access to a broad range of genetic material on which they can draw to develop more resistant and more productive varieties of plants and animals. The plant and animal gene pool, therefore, is a critical resource for achievement of sustainable agricultural production.

The literature on the role of genetic resources in agricultural development deals mainly with plants. That is the focus here also.

Present Status of the Resource

Hawkes (1985) assessed the status of the international system for managing plant genetic resources and found it generally good. The focus of the assessment was on the member institutions of the Consultative Group on International Agricultural Research (CGIAR) and on the 13 foodcrops for which they were at that time responsible. These crops include all those of importance at present in the world’s diet. Hawkes had a number of suggestions for improving the systems, but he concluded that, by and large, it was "...proceeding along the right lines" (p. 101) and that, apart from some rather mild criticisms,
"...the general record of the CGIAR in genetic resources work is very impressive indeed. Germplasm materials are being evaluated and utilized on a massive scale, and the results in terms of newly released varieties are outstandingly good... [Moreover] this study of the CGIAR system shows very clearly indeed that the genetic resources of the whole world are being made fully available to first, second and third-world countries on a scale that none of us had believed possible some fifteen to twenty years ago" (p. 102).

Hawkes sets up what he calls the Genetic Resources Impact Chain and he uses this to structure his assessment. The components of the chain are:

- Genetic resource surveys
- Exploration for and collection of plant genetic material
- Conservation of the resource
- Germplasm enhancement
- Breeding and trials
- National programs and release of varieties
- Well-being and economic enhancement of LDC farmers and countries
- Training
- Data bases
- Research

Hawkes evaluates the performance of each of the CGIAR Centers in each of these components. His evaluation is mixed, rather surprisingly so in view of the overall ringing endorsement quoted above. He found that most of the CGIAR institutions did a less than good job in collecting wild species related to their mandate crops. The institutions which he judged negligent on this score argue that all the genetic diversity needed can be found in the mandate crop itself, a view which Hawkes considers "short-sighted" (p. 96). Hawkes attributes the lack of concern for wild species to a lack of expertise in most of the institutions with respect to "... the taxonomy, geographical distribution, ecology, and evolutionary development of the [mandate] crop and its related wild species" (Hawkes 1985, p. 96).

Hawkes concluded that, on the whole, the institutions have done "fairly well" in conserving plant genetic resources, and that some of them have done "very well indeed" (p. 97). They get high marks for their work in evaluating genetic material, but are judged by Hawkes to have done a poor job in germplasm enhancement because of their neglect of wild species.

The institutions get high to very high marks with respect to breeding and trials, release of material to national programs, benefits to LDC farmers (although indicators here are hard to read), training of LDC scientists, and maintenance of data bases. Hawkes judges performance with respect to research on genetic resources to be mixed, good on tissue-culture conservation methods for potatoes, cassava and yams, but less impressive for other crops.
Hawkes also evaluated the performance of the International Board for Plant Genetic Resources (IBPGR), one of the Centers supported by the CGIAR. The IBPGR is not itself involved in plant research but has responsibilities for the promotion and diffusion of information about genetic resources. Among the components of the Genetic Resources Impact Chain, Hawkes judges that IBPGR generally has done well. He finds, however, that coordination between IBPGR and the different research institutions is not as good as it should be to achieve maximum benefits from the research accomplished.

McNeely et al. (1990) take a somewhat less sanguine view than Hawkes of the present status of the plant genetic resource and the system for maintaining it. Citing Plucknett et al. (1987), they note that, for many of the major world food crops such as wheat, maize, oats and potatoes, more than 90 percent of the genetic variation in landraces is now protected in seed banks, and that most of the work needed to do this for other species, such as rice, sorghum and millet, will have been done by 1990. However, citing Peeters and Williams (1984), McNeely et al. point out that, of the two million accessions of plant genetic material in seed banks around the world, an estimated 65 percent lack basic data on source, 80 percent lack data on such characteristics as methods of propagation, "and 95 percent lack any evaluation data such as responses to germinability tests. Extensive data are held on only one percent of the specimens, and it is feared that a substantial proportion of the accessions not tested for germinability might be dead" (McNeely et al. 1990, p.65).

McNeely et al. go on to note that the system of international and national seed banks has concentrated on crops of global importance so that species of only local or regional significance are poorly represented in the collections. Moreover, tree crops, e.g., rubber, cocoa and oilpalm, are poorly represented in the banks because they can only be conserved in facilities akin to botanical gardens; and among rootcrops only the potato is well represented in the banks because this crop must be planted every year to maintain the genetic strain, an expensive procedure. Finally, McNeely et al. agree with Hawkes that the managers of the seed bank system have given too little attention to collecting and preserving wild relatives of commercial crops. Except for a few crops, such as wheat, potato and tomato, wild germplasm is five percent or less of total seedbank collections. For example, wild relatives of rice and maize are two percent and five percent, respectively of total collections. How serious this low representation of wild relatives may be is disputed among crop breeders. McNeely et al. speculate that developments in biotechnology may increase the value of wild relatives by overcoming some of the technical difficulties which so far have restricted their role in crop breeding.

The Plant Quarantine Issue

It is not always sufficiently appreciated how dependent the world food system is on the international exchange of plant genetic material. Maize producers and consumers around the world are served by genetic material from Mexico and Central America; and the genetic resources used by cocoa producers in West Africa are found
in the western Amazon basin. Coffee producers in Brazil and elsewhere are dependent on wild relatives of the plant located principally in Ethiopia and Madagascar for the constant stream of new genetic material needed to maintain the vitality of the industry. Brazil, a supplier of wild rubber germplasm to rubber producers in Southeast Asia, receives genetic material from diverse sources globally to support its production of sugarcane, soybeans and other crops.

Over 98 percent of agricultural production in the United States is based on genetic material from elsewhere. In the Americas as a whole, half of total crop production is derived from genetic material native to Asia or Africa. Similarly, African crop production is 70 percent derived from Asia or the Americas, and Asian production 30 percent from American or African sources.\footnote{This and the preceding paragraph are based on McNeeley et al. (1990, p. 57).}

The system for maintaining plant genetic resources described by Hawkes (1985) recognizes the interdependence among regions for these resources. The interdependencies are reflected in an enormous transfer every year of plant material among countries. For example, in approximately ten years from the mid-1970s to the mid-1980s, ICRISAT, near Hyderabad, India, distributed over 4 million seed samples around the world (Plucknett and Smith 1988). The transfer inevitably carries the risk that plant diseases and pests will be spread to the receiving countries. Virtually every country has procedures to inspect and, if necessary, quarantine plant material to protect the nation against this risk. There is in this a potential conflict between plant breeders and quarantine managers. Breeders need ready movement of plant genetic material, both to expedite their own research and to disseminate the results of it to users. Quarantine managers operate under an imperative to protect their agriculture against the risk of imported diseases and pests. The potential conflict clearly has implications for the use of genetic resources to expand agricultural production.

Plucknett and Smith (1988) address this set of issues. They begin by citing much evidence that the international transfer of plant genetic material has, in fact, resulted in the spread of viruses that attack a variety of food crops. They note that 125 countries prohibit one or more plant species and over 240 crop or plant species are prohibited from entering at least one country. Some 1585 different pests and pathogens are targets of quarantine services worldwide (Plucknett and Smith 1988, p. 2). The services recognize that, given the massive movement of plant material and the difficulty of detecting many of the proscribed organisms, particularly viruses, they cannot eliminate the risk of contamination. Most aim at damage control rather than 100 percent protection.

The issue here is the extent to which the control measures may constrain the use of genetic resources to develop the new crop varieties that will be needed for successful response to the demand scenario. The study by Plucknett and Smith (1988) is relevant to this. After reviewing the history and current mode of operation of quarantine services, they make a number of suggestions to improve their performance and reduce the potential conflicts with plant breeders. One suggestion
is directed to the breeders themselves, or to the managers of germplasm banks worldwide. Many of the collections in these banks were assembled before quarantine controls were in place or diagnostic tools for detecting certain pathogens were available. Plucknett and Smith suggest that an important step would be to clean up these collections, notwithstanding the cost of doing this and the fact that many pathogens, particularly viruses, already are widely spread around the world. The potential damage from the further spread from these "dirty" collections would, they claim, justify the cost of cleaning them up.

The scientific skills and facilities required to efficiently manage quarantine services also need upgrading, particularly, but not only, in the LDCs. Plucknett and Smith point out that Nigeria was the only country with any effective quarantine facilities in the area stretching from West to Central Africa. Madagascar had only one quarantine officer and two assistants with training in plant pathology; and Brazil had only seven scientists, located in Brasilia, to handle quarantine operations for the entire country.

Plucknett and Smith assert that the investment cost of upgrading many quarantine services could be kept small by decentralizing operations and forging better linkages with universities. Steps should be taken also to increase the flow of information about crop pests and diseases to LDCs, where library facilities often are lacking. Plucknett and Smith note, however, that information exchanges over long distances could profitably be supplemented from time to time by personal contacts among crop breeders and quarantine service personnel. Workshops to provide such opportunities now are rare.

Finally, Plucknett and Smith emphasize two scientific aspects of the problem of providing adequate protection against the spread of pests and diseases without stifling the use of genetic material to develop new crop varieties. One is to promote more basic research on the biology and life cycles of pests and pathogens to permit quarantine services to do a more effective job in distinguishing among degrees of threat. The other scientific point concerns the development of new technologies for detecting pathogens. Plucknett and Smith note that this work is progressing rapidly, and that it offers much promise in permitting quarantine services to do a better job.

Conclusion About the Cereal-Crop Genetic Resource

The work of Hawkes and of Plucknett and Smith suggests a rather sanguine view of the present status and future prospects of plant genetic resources. The CGIAR system for management of these resource, including the transfer of improved material to national agricultural research systems, seems to be working reasonably well. Although the tension between crop breeders and quarantine services likely will be permanent, it does not seem to pose a major threat to the use of the resource. If the recommendations of Plucknett and Smith were adopted, the tension would diminish. Although McNeely et al. (1990) are more critical of the system for managing plant
genetic resources, their assessment is not fundamentally different from that of Hawkes.

There is, of course, no guarantee that the system will stay indefinitely in good health. Should funding for the CGIAR system decline, for instance, the vitality of the seedbank system likely would decline with it. But if funding remains adequate, and basic research on plant genetic behavior also is supported, then it seems that plant genetic resources should not seriously constrain the development of the more productive crop varieties that will be needed to respond adequately to the demand scenario. In reaching this view, it must be reemphasized that the focus of attention in the review has been on genetic resources directly applicable to foodcrop production and the wider and more challenging issues of biodiversity conservation and management in general have not been addressed here but are broached below in the discussion of environmental costs in Chapter 7.
CHAPTER 6

THE CLIMATE RESOURCE

Introduction

In Chapter 4 on water resources, we treated the climate resource as a given. That is, we assumed that regional climates around the world -- annual mean precipitation and temperatures and their variances, windiness, storm frequencies, and all other climate characteristics -- would remain as they now are over the period to 2030.

Expectations of Climate Change

There now is a strong scientific consensus, however, that the global and regional climates are likely to change over that period because of the enhanced warming effect of so-called greenhouse gases, carbon dioxide (CO$_2$), methane (CH$_4$), nitrous oxide (N$_2$O) and chlorofluorocarbons (CFCs). The combination of these gases is expected to increase global average temperatures some 2 to 4 °C from present levels by roughly the middle third of the next century (Parry 1990). It is expected that the increase will be greater at higher latitudes, that warming will be greater in winter than in summer and that global precipitation will increase because warmer air holds more water.

These expectations are based on results obtained from various global circulation models (GCMs) of the earth's climate. Typically these models are run assuming a "control" level of atmospheric CO$_2$ of 300 ppm to approximate the "pre-industrial" level of approximately 100 years ago, then run again with a doubled CO$_2$ level (2 × CO$_2$), and the results compared (Parry 1990).

The various GCMs give roughly similar results with respect to global averages, but they differ widely in their predictions of changing regional climates under 2 x CO$_2$ warming. The differences are wider with respect to precipitation than temperature. The differences about regional climates create great uncertainty about possible impacts on agriculture around the world. (There are also great uncertainties about both the amount and timing of global warming under 2 x CO$_2$, but these need not detain us here). There is strong reason to believe that agriculture in some regions will benefit from the expected climate change and that others will be disadvantaged. It is impossible, however, to predict with any confidence who may win and who may lose.

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1The literature on climate change has exploded in the past five years, and no effort was made to cover it in preparing this paper. Rather, we concentrate here on the earlier distillations of this literature by Martin Parry. He was lead author of the assessment of these consequences by the Intergovernmental Panel on Climate Change. His cited 1990 book is based on that assessment.
Although regional climate changes remain quite uncertain, there are, according to Parry (1990, p.16) "some continental-scale changes, consistently predicted by the high resolution GCMs, which are plausible." Warming, for example, is expected to be 50-100 percent greater than the global mean in high northern latitudes in winter, and precipitation to increase in middle- and high-latitude continents in winter. Evaporation rates will increase with higher temperature, indicating less soil moisture over much of the globe, especially in the mid-latitude mid-continental regions during northern hemisphere summer (e.g., the American Midwest).

Case Studies of Climate Change

Despite the many uncertainties, the International Panel on Climate Change (IPCC) did case studies of five large regions to estimate possible changes in temperature and precipitation. The studies assumed an increase in global mean temperature of 1.8°C by 2030. Parry (1990), whence this account is taken, warns that confidence in the estimates is low, especially for changes in precipitation and soil moisture (the most critical variables for agriculture). Following are some of the results of the model runs (Parry 1990, p. 17).

**Central North America (35-50°N, 85-105°W)**

Warming varies from 2 to 4°C in winter and 2 to 3°C in summer. Precipitation increases from 0 to 15 percent in winter and decreases 5 to 10 percent in summer. Summer soil moisture declines 15 to 20 percent.

**Southeast Asia (5-30°N, 70-105°E)**

Warming varies from 1 to 2°C throughout the year. Precipitation changes little in winter, but increases generally 5 to 15 percent throughout the region. Summer soil moisture increases 5 to 10 percent.

**Sahel (10-20°N, 20°-40°E)**

Warming ranges from 1 to 3°C. Mean precipitation increases and soil moisture decreases marginally in summer. However, there are areas of both increase and decrease in both temperature and precipitation throughout the region.

**Southern Europe (35-50°N, 10°W-45°E)**

Warming is about 2°C in winter and 2 to 3°C in summer. Some indication of more precipitation in winter, but summer precipitation is down 5 to 15 percent and summer soil moisture decreases 15 to 25 percent.
Australia (10-45°S, 110-155°E)

Warming is 1 to 2°C in summer and about 2°C in winter. Summer precipitation increases about 10 percent, but the models produce inconsistent estimates of changes in soil moisture. Large sub-continental variations around the averages.

The errors (presumably as measured by the coefficient of variation) on these estimates range from 70 to 145 percent.

Additional modeling work focused specifically on soil moisture found the following (Parry 1990, p. 19):

a. Decreases in soil moisture in December, January and February in
   - Northeast and southern Africa
   - Western Arabian peninsula and Southeast Asia
   - Eastern Australia
   - Southern USA
   - Argentina pampas

b. Decreases in soil moisture in June, July, and August in
   - North and West Africa
   - Parts of western Europe
   - North and Central China, parts of Central Asia and Siberia
   - Southern USA and Central America
   - Western Australia.

Consequences for Agricultural Production

What might all this mean for agricultural production? Because of the great uncertainty about regional climate change, no clear answer is possible. Studies of climate change impacts on agriculture have focused on temperate zone countries and regions, especially North America and Europe (Parry 1990, p. 65). The studies suggest that the impacts would be favorable in northern Europe, unfavorable in southern Europe.

In the U.S., the Environmental Protection Agency supported a comprehensive study of impacts on agriculture, drawing on two of the better-known GCMs. The models showed higher temperature and lower soil moisture for most areas of the country resulting in lower yields for all the major non-irrigated crops. However, the crop “fertilization” effects of higher atmospheric CO₂ offset some of the yield decline. When the yield effects were entered into a nationwide crop production model, the
result was a decline in production for most crops, especially sorghum (-20 percent), maize (-13 percent) and rice (-11 percent). The model, however, did not take account of possible production and price changes elsewhere in the world, so they are no more than crude first approximations to possible production consequences in the U.S.

Subsequent to the EPA study, the U.S. Department of Agriculture did a study of the production and price effects of climate change on the global agricultural economy (reported in Parry 1990, pp. 111-18). Given the many uncertainties entailed in this undertaking, from the climate models themselves, through the regional yield effects, to the production and price responses, the results of this exercise have to be treated with caution. For what they are worth, the results show that, if climate change reduces crop yields in the U.S., the European Community and Canada on the scale suggested by the EPA model for the U.S., then world food prices over the next 50 years would vary between being about the same as at present and being 50 percent higher, depending on compensating production increases or reinforcing decreases elsewhere around the world (Parry 1990).

Finally, one recent careful modeling study of the effects of climate change on rice production (Penning de Vries 1992) reveals insignificant changes in the warmest regions of the rice-growing world and possibly small (at most a few percent gain in yield) but uncertain changes in other regions.

The Importance of Adjustments

A major limitation of all these climate impact studies, which Parry is careful to point out, is that they make no allowance for the technical, managerial and institutional adjustments, on and off the farm, which surely would occur in response to climate change. Farmers have had to adjust to climate fluctuations for as long as there has been settled agriculture, and much of the effort of crop breeding programs around the world has been aimed at developing varieties better adapted to climatic conditions. Although there can be no certainty about this, the expectation of atmospheric scientists is that the climate will change gradually, and on a time scale that is long by comparison with the time scale for investments in agriculture (except for large dam projects). There is good reason to believe, therefore, that farmers and the rest of the agricultural community will have ample time to make adjustments to climate change.

Results of research at Resources for the Future (reported in Easterling, McKenney, Rosenberg and Lemon 1991 and Crosson and Katz 1991) show that these adjustments can make a very substantial difference in the impacts of climate change on agriculture. The research focused on the four U.S. states of Missouri, Iowa, Nebraska and Kansas (MINK) and asked the question, what would happen to agricultural production in this region in 2030 if the climate changed gradually and permanently to replicate that of the 1930s (the "dust bowl" years). The 1930s were chosen because they were hotter and dryer than the present climate, as most GCMs predict for the central U.S. with global warming, and because there was a regionally detailed climate record for that period. Using the EPIC model, (Chapter 3) the research showed that, under the 1930s climate and before allowance for CO₂ enrichment and
on-farm adjustments, yields of maize, sorghum and soybean (but not wheat) would be lower in 2030 by percentages comparable to those found in the EPA study, mentioned above. Allowing for CO₂ enrichment offsets some of this decline, as in the EPA study. But the major offsetting effect resulted from on-farm adjustments to the hotter and dryer climate. These adjustments were of two sorts: (a) adoption of off-the-shelf practices that are not economical under the existing climate but would be under the changed climate, e.g., a shift to earlier spring planting and use of longer-season varieties to compensate; and (b) development of new varieties and practices especially designed for production under the hotter and dryer climate by regional agricultural research institutions.

When the CO₂ enrichment effect and on-farm adjustments were allowed for, the initial decline in regional crop production of 20-25 percent was converted into a small increase. The RFF researchers emphasize that the specific numerical results of their work should not be taken too seriously, but that the direction of the effect of adjustments should be. Farmers and agricultural research institutions all around the world have demonstrated a capacity for adaptations to climate that cannot be ignored when considering likely impacts of climate change. There can be no serious doubt that, after allowance for adaptation, the production and price consequences of climate change would be less severe than indicated by the modeling work described above.

Summary and Conclusion

There is a strong scientific consensus that the global climate will change as a consequence of increasing atmospheric concentrations of "greenhouse" gases. There is great uncertainty, however, about the amount and rate of change. There is even greater uncertainty about how regional climates may change, especially with respect to precipitation. Hence all predictions of the global and regional impacts of climate change on agriculture must be viewed with great scepticism. The present state of knowledge indicates that some regions will benefit and some will suffer from climate change, but no one can confidently predict who the winners and losers may be. On a global scale, the modeling work done so far suggests that agricultural production would be little affected (winners and losers offset each other) or could decline (losers dominate winners). All of this work, however, ignores the adjustments that farmers and institutions will make to climate change. Whatever the negative effects now indicated by the global modeling results, they would be less negative, conceivably even positive, when account is taken of adjustments.

Thus, given the present state of knowledge, consideration of prospective changes in global and regional climates and their consequences does not suggest that on a global scale the supply of climate resources will diminish or increase from present levels. The prospects for climate do, however, reinforce the arguments advanced below in Chapter 9 about the importance of strengthening the capacity of institutions to improve resource management and to develop new agricultural technologies.
CHAPTER 7

ECONOMIC AND ENVIRONMENTAL COSTS

Introduction

This chapter addresses the question: Over the next 40 years what would be the effect on economic and environmental costs of global agricultural production of seeking to meet the demand scenario within the existing knowledge regime? Another way of phrasing the question is this: Holding the supply of knowledge resources fixed, what would be the economic and environmental costs of meeting the demand scenario by increasing supplies of land, water, and genetic resources, and assuming that the supply of climate resources, on a global scale, is unchanged?

No attempt is made to estimate economic and environmental cost quantitatively. This would be a task quite beyond the scope of this paper, even if the data and models for estimating such costs were available, which they are not. Work done by Binswanger (1989) is suggestive, however, of the possible impact of the demand scenario on economic costs if the supply response of farmers was limited only to bringing more land, water and other resources into production within the existing knowledge regime. Drawing on his own research and that of others in estimating short-run supply elasticities for wheat and several other crops in semi-arid India, Binswanger found the aggregate elasticities to range from 0.05 to 0.09. Binswanger states that these aggregate elasticities are consistent with comparable estimates in other countries. The elasticities can be interpreted as indicating that, to elicit a short-term increase in supply of 5 to 9 percent, crop prices would have to increase 100 percent. Our demand scenario shows almost a doubling of global demand for crops and a 2.7 times increase in the LDCs. If farmers could respond to these increases only by tapping the earlier indicated potential supplies of land, water, and related resources, we would expect the supply elasticities to be greater than those for the short-run shown by Binswanger, but considerably less than if the potential supplies of land and water were more abundant and allowance could be made for increased supplies of knowledge resources. But even if these "intermediate-term" supply elasticities were double those Binswanger found -- say 0.1 to 0.2 -- inducing farmers to double global output would require a 500 percent to 1000 percent increase in global crop prices. Such increases surely would be viewed as unacceptably high throughout the world community.

These calculations are consistent with one's intuition that, given the potential supplies of land and water in the less-developed world, and no increase in supplies of knowledge resources, then the demand scenario would imply steeply rising economic costs of crop production over the next 40 years. In what follows, we marshall such skimpy evidence as is available to check this intuition further, with respect to both economic and environmental costs.
It may be useful to remind the reader of the meaning of holding the supply of knowledge resources constant. It means no changes in policies and institutions to encourage more efficient use of present knowledge by farmers, no investment in new social science knowledge relevant to agriculture, and no investment in special training or higher education to deepen the human capital engaged in agriculture.

Meanings of Economic and Environmental Costs

Economic costs are those reflected in market transactions for agricultural resources and outputs. They are represented, therefore, by agricultural commodity prices. Environmental costs are not reflected in market transactions (for reasons discussed below) and, therefore, are unpriced.

Some economic costs are paid by the farmers generating them, but others are not. For example, farmers bear the cost of their own or hired labor, but not the downstream costs of reduced crop yields because of salts in their irrigation return flows. Environmental costs, however, are borne exclusively by others, not by the farmer who generates them. Table 7.1 depicts this relationship between economic and environmental costs.

Table 7.1: Relationship Between Economic and Environmental Costs of Agricultural Production

<table>
<thead>
<tr>
<th>Kind of Cost</th>
<th>On-farm</th>
<th>Off-farm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic (priced)</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Environmental (unpriced)</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

Thus all economic costs are reflected in commodity prices but some are not paid by the farmer who generates them. All environmental costs are unpriced by definition, and none of them is paid by the farmer who generates them. (If they were priced, they would be reflected in the farmers' economic costs of production, and hence would not be environmental costs.)

1On-farm erosion-induced losses of soil productivity sometimes are called environmental costs. However, these losses are conceptually no different from those resulting from the depreciation of farm machinery or any other asset. They are properly counted, therefore, as economic, not environmental costs.
Economic Costs

Because economic costs are reflected in agricultural commodity prices, our statements about the effects of the demand scenario on these costs will be in terms of whether commodity prices (adjusted for inflation) would be likely to rise, fall or remain the same.

Supplies of land. In Chapter 3, estimates were presented showing that the amount of land in the world now in forest and range with potential for crop production is approximately equal to the amount of land now in crops. Some 85 to 90 percent of this land is in the LDCs. Discussion of the estimates indicated, however, that they almost surely overstate, probably by a considerable margin, the quantity of range and forest land that could be economically converted to crop production at current prices. But how much might be so converted? Any answer must be highly speculative. We have nevertheless made bold to engage in such speculation because our assessment in Chapter 9 of the potential for new technological knowledge requires us to do so. The results of this speculative enterprise are in Table 7.2.

The uncertainty about every number in Table 7.2 is considerable, but some judgment needs to be made about the broad possibilities and these judgments seem to us to be vaguely "sensible" and of the likely probable orders of magnitude. Although much more investigation clearly is required to make any such claims defensible, such an effort was beyond the scope of this report.

For what it is worth, the projected 0.8 percent increase per year in cultivated land would cumulate to a 43 percent increase between 1985 and 2030. Compare this with the demand scenario showing a 169 percent increase in crop consumption in the LDCs between 1988/89 and 2030 (Table 2.3).

The future supply of cropland might also be increased by reducing the productivity damages of soil degradation. In Chapter 3, we made no estimates of these present and prospective effects of soil degradation except in the U.S. where the effects are small. The available data do not permit comparable estimates for other countries. However, if the cumulative loss of soil productivity in the LDCs over the next 50 years were five times the maximum 50-year loss estimated for the U.S. (about 5 percent, see Chapter 3), completely eliminating the losses would increase land supply only 25 percent. Moreover, studies done by the U.S. Department of Agriculture indicate that the marginal costs of reducing erosion-induced productivity losses rise steeply as the amount of loss gets smaller. If erosion control to drive the losses in LDCs to zero would add some 25 percent to land supply by 2030 or 2040, the economically-feasible increase in supply surely would be less than that.

With the quantity of cropland in the LDCs that could be economically converted to cropland by 2030 at present crop prices only 40-45 percent greater than the present quantity of such land, and with the production potential from reduced soil degradation probably much less than this, there is no way the 169 percent crop consumption increase projected for those countries in the demand scenario could be accommodated.
Table 7.2: Realizable Increases in Cultivated Area

<table>
<thead>
<tr>
<th></th>
<th>Africa</th>
<th>S.W. Asia</th>
<th>S.E. Asia</th>
<th>Central Asia</th>
<th>South America</th>
<th>Central America</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium-term incremental exploitation (%)</td>
<td>25</td>
<td>0</td>
<td>50</td>
<td>60</td>
<td>20</td>
<td>50</td>
<td>24</td>
</tr>
<tr>
<td>Present (Table 3.4) (mill. ha)</td>
<td>168</td>
<td>69</td>
<td>274</td>
<td>113</td>
<td>124</td>
<td>36</td>
<td>784</td>
</tr>
<tr>
<td>Total scenario cultivated area by 2030 (mill. ha)</td>
<td>323</td>
<td>69</td>
<td>286</td>
<td>121</td>
<td>263</td>
<td>55</td>
<td>1117</td>
</tr>
<tr>
<td>Rate of change per year at constant rate to 2030 (%)</td>
<td>1.5</td>
<td>0.0</td>
<td>0.1</td>
<td>0.2</td>
<td>0.7</td>
<td>0.9</td>
<td>0.8</td>
</tr>
</tbody>
</table>

* Percentage of presently uncultivated potentially arable land (Table 3.4) that may be exploited for crops by 2030.
* Row 1 of this table times row 3 of Table 3.4 plus row 2 of Table 3.4
* The constant proportional rate of growth to reach row 3 from row 2 of this table over 45 years.
* Weighted sum of exploitation rates.

With present supplies of knowledge about crop production. Some of the pressure on LDCs' land resources could be eased by imports from MDCs, where demand pressures would be less and land resources more abundant. But a substantial land constraint in the LDCs surely would remain. It follows that, given the existing supply of knowledge resources, the demand scenario implies strong pressure on the supply of land in LDCs, tending, in turn, to raise their economic costs of crop production.

**Supplies of water.** Although global warming is generally expected by climatologists, and should increase global average precipitation, the regional effects on precipitation, runoff and soil moisture cannot be reliably forecast. In some regions, precipitation may increase the supply of water for agriculture, but in other regions precipitation likely will decrease.

With or without climate change, the discussion in Chapter 4 indicated that the potential increase in land that could be profitably irrigated at current crop prices probably would be substantially less than the 50 to 55 percent shown in Table 4.2. Given the existing supply of knowledge resources, additional irrigated production would fall well short of that needed to satisfy the demand scenario at acceptable costs.

**Genetic resources.** The literature reviewed in Chapter 5 indicated that the international system for maintaining the plant gene pool needed for continuing development of new crop varieties works reasonably well. The main reservation was about the system's inattention to collecting and preserving wild races of plants related to those now in
economic production around the world. It did not appear, however, that the reservation was inconsistent with the conclusion that the supply of plant genetic resources would prove adequate to support rising global crop production at no increase in economic costs. In the context of the preceding discussion, this is to say that the demand scenario likely implies rising economic costs because of land and water supply constraints, but not because of limitations in the supply of genetic resources.

Environmental Costs

General. Recall that the environmental costs of agricultural production are unpriced and that all of them are paid by someone other than the farmer who generates them. Environmental costs include such things as downstream damages of sediment and agricultural chemicals to household, industrial, and recreational uses of water, accelerated siltation of reservoirs with resulting losses of flood-control and power-generation benefits, and losses of plant and animal habitat when forests are cleared and wetlands drained to produce crops. These costs are not included in the prices of commodities because they occur off the farm under institutional conditions in which farmers do not have to pay. The key condition is that those bearing the costs do not have an enforceable property right in the resource suffering damage, so they cannot charge farmers a fee to cover the cost of the damage. For example, owners of a downstream recreation site typically have no property right in the stream running through or adjacent to a farmer’s field upstream, so they cannot charge a fee for using the stream as a dump for sediment and agricultural chemicals. Similarly, many of the people who value wildlife and plant species dependent on tropical forest habitat are scattered all over the world and have no property right in forests being cleared for agricultural production. They cannot, therefore, charge a fee to the forest clearers representing the loss of habitat value.

Because farmers do not bear environmental costs, they treat them as zero. As profit maximizers, within the economic, cultural and institutional constraints relevant to them, they will seek to manage their resources so as to equate the marginal costs and benefits of each resource. Since the resources that bear environmental costs, e.g. the river as a dump for sediment, have zero marginal cost to the farmer, he or she will use them to the point where their marginal value to the farmer also is zero. From the standpoint of the farmer, this is optimal use of the resource because it corresponds to the efficiency criterion: equate marginal costs and benefits. But from the standpoint of society, the farmer’s use of the resource is excessive because the marginal social cost of use is positive and the marginal social value -- the return to the farmer -- is zero.

The existence of environmental costs is clear enough (although they were not generally recognized, at least by economists, as recently as 30 years ago), and the generic conditions that bring them about are reasonably well understood. But knowledge of the present magnitude of the costs on a global scale and for any given country is minimal. The reason is that environmental costs are not registered in market
transactions, at least not explicitly, so they leave no monetary trail by which they can be traced, measured and compared with other costs.

Because of the variety of environmental costs of agricultural production and the scarcity of information about them, a full treatment of the costs is not attempted here. Instead we focus on three important categories of cost: those resulting from pesticide use, from sediment damage, and from losses of biological diversity because of land clearing and drainage. This leaves out some costs, e.g., losses of recreational values from fertilizer-induced eutrophication of lakes and reservoirs, but the literature suggests that the three considered probably are most important, at least in LDCs.

**Costs of pesticides.** The problem of measuring environmental costs is well illustrated by the case of pesticides. Pesticides are designed to kill things: weeds, insects and fungi. Over the past four decades, they have done this very well and, in the process, made an enormous contribution not only to increased world food production but also to human health, e.g., through control of the malaria-carrying mosquito. But pesticides often affect unintended as well as intended targets and can, therefore, be a threat to human health, wildlife, and whole ecological systems. It is these unintended damages that constitute environmental costs of pesticides. One can find numerous accounts of these costs in terms of human illnesses and deaths, number of fish killed, the build-up of genetic resistance to insecticides among insects, thus thwarting control efforts, and other instances of these costs. But nowhere are there comprehensive estimates of the monetary value of the costs that provide a basis for judging their importance relative to other costs of agricultural production, or their trend over time.

With respect to trend, there are some data which suggest that whatever the environmental costs of pesticides are, they may have declined in some countries from the late 1970s to the early 1980s, and increased in others. The data are from a report by the World Resources Institute (1990), and are shown in Table 7.3. For all major regions, data are included for all countries for which data were available for both sets of years and which showed at least 1000 t of use in at least one of the two sets. This included 8 of 49 African countries, 12 of 15 countries in North and Central America, 11 of 12 countries in South America, 13 of 37 Asian countries and 24 of 27 European countries. Malaysia, with 9730 t of use in 1982/84 but no use reported for 1975/77, was the largest user not included in the table.

In 1982/84, the then USSR, the USA and China, in that order, were the largest total users of pesticides. Between them these three countries accounted for 49 percent of total usage by the countries included in the table. By intensity of use, measured by kg/ha of cropland, Italy, Egypt, Greece and Japan were the biggest users. The country data indicated that, among major regions, intensity of use was greatest in Europe, although regionwide measures of use per hectare are not available.
Table 7.3: Pesticides used 1975/77 and 1982/84

<table>
<thead>
<tr>
<th>Region</th>
<th>Mass of Active Ingredients 1975/77 (kt)</th>
<th>Mass of Active Ingredients 1982/84 (kt)</th>
<th>Per unit of cropland 1982/84 (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFRICA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Algeria</td>
<td>16.0</td>
<td>21.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Egypt</td>
<td>27.0</td>
<td>19.6</td>
<td>7.6</td>
</tr>
<tr>
<td>S. Africa</td>
<td>19.3</td>
<td>11.6</td>
<td>0.8</td>
</tr>
<tr>
<td>Tanzania</td>
<td>3.0</td>
<td>5.8</td>
<td>1.1</td>
</tr>
<tr>
<td>N. &amp; CENTRAL AMERICA</td>
<td>529.6</td>
<td>487.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Canada</td>
<td>27.0</td>
<td>54.8</td>
<td>1.2</td>
</tr>
<tr>
<td>Cuba</td>
<td>7.9</td>
<td>9.6</td>
<td>2.8</td>
</tr>
<tr>
<td>Guatemala</td>
<td>4.7</td>
<td>5.1</td>
<td>2.7</td>
</tr>
<tr>
<td>Mexico</td>
<td>19.1</td>
<td>27.7</td>
<td>1.1</td>
</tr>
<tr>
<td>U.S.</td>
<td>459.4</td>
<td>373.3</td>
<td>2.0</td>
</tr>
<tr>
<td>S. AMERICA</td>
<td>108.0</td>
<td>99.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Argentina</td>
<td>7.4</td>
<td>14.3</td>
<td>0.6</td>
</tr>
<tr>
<td>Brazil</td>
<td>59.3</td>
<td>46.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Colombia</td>
<td>19.3</td>
<td>16.1</td>
<td>3.0</td>
</tr>
<tr>
<td>Ecuador</td>
<td>5.4</td>
<td>3.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Venezuela</td>
<td>7.0</td>
<td>8.1</td>
<td>2.1</td>
</tr>
<tr>
<td>ASIA</td>
<td>287.4</td>
<td>320.8</td>
<td>1.6</td>
</tr>
<tr>
<td>China</td>
<td>150.5</td>
<td>159.3</td>
<td>1.6</td>
</tr>
<tr>
<td>India</td>
<td>52.5</td>
<td>53.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Indonesia</td>
<td>18.6</td>
<td>16.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Japan</td>
<td>34.0</td>
<td>32.0</td>
<td>6.8</td>
</tr>
<tr>
<td>Thailand</td>
<td>13.1</td>
<td>22.3</td>
<td>1.1</td>
</tr>
<tr>
<td>EUROPE</td>
<td>506.9</td>
<td>585.4</td>
<td>5.1</td>
</tr>
<tr>
<td>France</td>
<td>83.0</td>
<td>98.8</td>
<td>5.1</td>
</tr>
<tr>
<td>Greece</td>
<td>30.6</td>
<td>29.2</td>
<td>7.4</td>
</tr>
<tr>
<td>Italy</td>
<td>84.0</td>
<td>98.5</td>
<td>8.1</td>
</tr>
<tr>
<td>Romania</td>
<td>29.4</td>
<td>17.2</td>
<td>1.6</td>
</tr>
<tr>
<td>Spain</td>
<td>55.3</td>
<td>71.6</td>
<td>3.5</td>
</tr>
<tr>
<td>USSR</td>
<td>348.8</td>
<td>535.4</td>
<td>2.3</td>
</tr>
<tr>
<td>AUSTRALIA</td>
<td>60.6</td>
<td>65.2</td>
<td>1.4</td>
</tr>
</tbody>
</table>

As indicators of costs of pesticide damage, the data in Table 7.3
tell nothing for any single country for either set of years. Among countries, higher
numbers for either year may indicate higher potential costs, and for any country
changes between the two sets of years may indicate changes in potential costs. But
these statements must be interpreted with great caution because the data tell nothing
about either the conditions of use, e.g., weather conditions at the time of application,
use of protective clothing and other precautions, or about the damage potential of the
materials. It is widely believed that fewer precautions in use are taken in LDCs than
in more-developed, suggesting that costs per kilo of use may be higher in LDCs.

Several features of pesticide use in the United States suggest that
environmental costs of pesticides may have declined in that country between the two
sets of years shown in Table 7.3. The 19 percent decline in total use from 1975/77
to 1982/84 is one such feature. In addition, herbicides, which generally are less
threatening to animals than insecticides, increased as a percentage of total use; and
among insecticides the trend was toward less persistent, although more acutely toxic,
material. Although greater acute toxicity carries the risk of greater damage to those
affected, it also makes the damage more quickly evident and, therefore, more readily
managed than for less immediately toxic but more persistent material, such as DDT.
In fact, the costs of highly toxic pesticide damage to people and other unintended
targets seem more akin to costs of industrial accidents than to true environmental
costs. Because toxic pesticide damage typically is immediately evident, e.g., poisoning
in the process of application, the risks of damage can be assessed and reflected in the
wages paid to the farm workers at risk. In this case, the costs would be reflected
largely in agricultural production costs, making them economic, not environmental
costs.

The damages of persistent, low toxicity pesticides such as DDT cannot typically
be traced to their source; and in any event, those who feel themselves damaged by
such materials, e.g., people who value wildlife whose life cycle is disrupted by
ingestion of the materials, have no property right in farmers' use of the materials and
cannot, therefore, force farmers to bear the costs of the damage.

Whether the trends in pesticide use in the United States -- aside from the
change in total use -- are present in other countries or regions of the world cannot be
determined from the available data and other information. It is relevant to note,
however, that a recent report (World Bank 1992) on environmental issues in China
states that that country is a world leader in research on integrated pest management,
that is, on systems of pest (mainly insect) control which seek to reduce the use of
inorganic pesticides by applying them only when insect populations are large enough
to threaten economic damage to the crop, and by substituting biological controls for
pesticides. China has a national pest surveillance and monitoring system that is used
to advise farmers when it is economical to apply pesticides. Although China's pest
management research is at an early stage and faces problems of under-funding, it
looks promising (World Bank 1992). Given that country's position as the third largest
user of pesticides (Table 7.3), its efforts to devise less environmentally threatening
methods of pest management are encouraging.
Although the present levels and trends in environmental costs of pesticides are not known for any country, it seems reasonably clear that, with the supply of knowledge resources fixed, the demand scenario for 2030 would induce farmers around the world, particularly in LDCs, to increase the application of pesticides, both in total and per hectare. A doubling of global food demand and a 2.7-times increase in LDCs would seem certain to stimulate this response, in the absence of new knowledge about pest management. In this event, the probability of rising environmental costs of pesticides over the next 40 years would appear high.

**Sediment.** Eckholm (1976) published evidence of substantial damages from sedimentation in countries all around the world, but especially in LDCs. He noted increased flooding in the Indus plain of Pakistan, in parts of India, Thailand, the Philippines, Indonesia, Malaysia, and in the Cauca Valley of Colombia, and he attributed it to rising streambed levels because of sediment from eroded land upstream. Eckholm also noted that accelerated siltation of the Mangla reservoir in Pakistan has reduced the expected life of the facility by one-third to one-half, and that reservoirs in other Asian countries also were threatened.

Some of the sediment causing such damages resulted from the cutting of trees for firewood and the building of roads in mountainous areas, but much of it also must have reflected land clearing to grow crops and graze animals. No one knows the relative importance of these various sources of sediment damage.

Eckholm’s evidence was anecdotal and did not provide the basis for a comprehensive estimate of the costs of sediment damage in either MDCs or LDCs. Subsequent studies have not filled this knowledge gap, although they appear to support Eckholm’s argument that costs of sediment damage are high, particularly in LDCs. The India Department of the World Bank (1991a), for example, cited a study of eight reservoirs in India, which found that rates of siltation are substantially higher than design rates, and that on average actual reservoir life will be only 35 percent of the design life unless siltation rates are reduced. The India Department’s report noted that the effect of this on the economic value of the reservoirs nevertheless could be small if their design life were long. For example, cutting the life from 200 years to 70 years -- 35 percent of the design life -- would have little effect on the economic present value of the reservoir because of discounting. Whether this calculation would capture all the environmental costs of sedimentation of the reservoirs, e.g., losses of recreational or habitat values, cannot be discerned in the India Department’s report.

The previously mentioned report on environmental issues in China (World Bank 1992) cited Chinese sources as stating that in the country’s region of loess soils (530,000 km², about 5 percent of the country’s total area) sediment was raising the bed of the Yellow River by 10 cm annually, thus increasing the incidence of flooding and affecting the lives of 100 million people living in flood-prone areas. The same report also stated that, in the country’s Guangxi province, sedimentation has reduced the provincial irrigation system to 30 percent of its planned capacity.
D. J. Gunaratnam, in a personal communication with S. Barghouti, has observed that, in the three decades ending in 1989, China made rather impressive progress in controlling erosion in the Yellow River basin, reducing the sediment load of the river by over 200 Mt/y through a combination of afforestation, terracing and construction of check dams in gullies.

We have discovered no other data suggesting trends in sediment loads in other countries, let alone trends in environmental costs of sediment. As in the case of pesticides, however, it appears that farmers' responses to the demand scenario would increase sediment costs. With the supply of knowledge resources fixed, farmers inevitably would respond to the growth of demand by converting forest and range land to crops. Historically this has increased erosion and sedimentation. Although more sedimentation does not necessarily imply higher environmental costs, the scale of the response to the demand scenario almost surely would force a rise in costs.

Biological diversity. Chapter 5 on genetic resources noted the importance of maintaining the resource as the genetic base for developing new crop varieties. It was also concluded in the chapter that the system for protecting the plant genetic resource works reasonably well and that future supplies of the resource should not seriously limit the production response to the demand scenario.

But the plant genetic resource relevant to crop production is only a small part of the plant and animal gene pool of present and future value to human beings. Wilson (1989, p. 108) refers to this pool as the store of "biological wealth" and describes it as "... a potential source for immense untapped material wealth in the form of food, medicine and other commercially important substances".

Neither Wilson nor anyone else has attempted to place a value on this stock of biological wealth, but Wilson's assessment of its importance is widely shared. One of the problems of valuing the stock, and judging the seriousness of threats to it, is that the number of species in the stock is unknown. Wilson, with help from other specialists, estimated the number of named species to be 1.4 million. But, he asserts, even conservative estimates put the total number of species at 4 million, and he cites research results in tropical Brazil and Peru which, when extrapolated globally, produced an estimate of 30 million.

Whatever the size of the biological pool, there is general agreement that maintaining it at some level is important for human welfare in the same sense that maintaining the plant genetic resource for crops is important. There is no agreement, however, about what that level should be. Some people -- Wilson appears to be among them -- seem to believe that any species loss poses a threat to future welfare because any species may, in time, prove to have unique social value. Others -- most economists appear to be among them -- take a much more relaxed view of species loss, although most of these likely would accept that, at some point, the social costs of loss would exceed the costs of preventing further loss. The professional bent of economists to think in terms of substitution among resources may account for their reader acceptance of, if not complacency about, species loss.
The social value of species lost as a result of agricultural production is an environmental cost of production because the lost species value is not priced. It is not priced for the same reason that other environmental costs are not priced: those who value the species have no property right in it, and, therefore, cannot control the activities that lead to its extinction.

As no one knows how many species there are in the world, so no one knows the rate at which they are being lost. The World Resources Institute (1990, p.8) asserts that "...careful estimates are that we are losing 100 species per day" but such estimates have to be viewed with deep scepticism.

Without attempting quantitative estimates, McNeely et al. (1990, p.41) cite Wilson (1988, p.41) as the authority for an assessment that "...by many indications, the world is already experiencing extinction rates of greater scale and impact than at any previous time in the earth’s history." In the same context, McNeely et al. (1990, p.41) state that

"The rapid destruction of the world’s most diverse ecosystems, especially in the tropics, has led most experts to conclude that perhaps a quarter of the earth’s total biological diversity is at serious risk of extinction during the next 20-30 years".

Forest clearing to produce crops or graze animals is the agricultural activity that is most likely to contribute to species loss. As the statement above suggests, tropical deforestation is of particular concern. Estimates of the rates of tropical deforestation (from all sources, not just agriculture) vary widely. McNeely et al. (1990, p. 45) present a table based on FAO data, showing that, in tropical Africa, Asia and America, about 0.6 percent of the forested area is being cut every year in each region. McNeely et al. assert, without supporting evidence, that while these estimates generally are believed to be the best available, most sources consider them to be "...far below actual rates of deforestation" (McNeely et al. 1990, p.45). According to the estimates, 20 percent of all tropical deforestation is in Brazil, where the annual cut is 0.4 percent of the total forested area. The next highest annual cut is in Colombia, where it is 1.8 percent of the country’s forested area and 12 percent of global annual deforestation in the tropics. On a regional basis, 56 percent of all tropical deforestation is in Latin America, 25 percent is in Asia and 19 percent is in Africa. About 16 percent of all the deforestation in Africa is in Zaire.

Preliminary estimates of tropical forest area and the rate of deforestation for 87 countries in the tropics were presented at the 10th World Forestry Congress in September 1991 by the Forest Resources Assessment 1990 Project (1991) of the FAO. Presenting estimates of total forest area for 1980 and 1990, an annual rate of deforestation between 1981 and 1990 of 0.9 percent is reported, nearly half of which occurs in Latin America, 30 percent in Africa and about 20 percent in Asia. These revised calculations vary dramatically from the 0.6 percent per annum deforestation rate estimated by the FAO/UNEP assessment published in 1980.
There is great uncertainty about all of these estimates, global and regional, as well as for individual countries. In a summary statement about the quality of these data, McNeely et al. (1990, p.44) assert that "...estimates of world forest cover and deforestation rates suffer from a surprising lack of firm statistics," although the reasons for surprise are not given.

The concern about the effects of tropical deforestation on biological diversity reflects the extraordinary biological richness of these habitats. McNeely et al. (1990) point out that tropical moist forests cover only 7 percent of the earth's land surface but contain at least 50 percent of the earth's species, and perhaps much more. To illustrate this richness, they cite a study in a lowland tropical rainforest in Costa Rica where 233 species of vascular plants were counted in an area of 100 m². This is equivalent to about one-sixth the total flora of the British Isles.

The poor quality of the data on tropical deforestation and on whatever losses of biological diversity this might entail, does not permit confident judgments about trends in the environmental costs of diversity losses. With respect to the future, McNeely et al. (1990) believe that rising world population and economic activity are likely to increase the rate of deforestation. We believe this is the implication also of our demand scenario. In responding to that scenario, given no increase in knowledge resources, farmers in tropical areas likely will have incentive to continue to clear land for crop and livestock production. One likely consequence would be rising costs of losses in biological diversity.

Conclusion on Economic and Environmental Costs

The discussion of the two kinds of costs points unequivocally to the conclusion that, with the supply of knowledge resources fixed, the demand scenario would imply rising economic and environmental costs of agricultural production, probably in all countries with an active agricultural sector, and with virtual certainty in the LDCs. On a global scale and in most countries the supplies of land and water could not be increased enough to accommodate the demand scenario at current commodity prices; and the drive to increase production inevitably would result in increased use of agricultural chemicals and land clearing with consequently rising environmental costs.

There is no basis for estimating how much costs might rise. We believe, however, that the increase would generally be regarded as unacceptable and would stimulate efforts to contain the costs. These efforts can be thought of as designed to increase the supply of knowledge resources to raise the productivity of the more limited supplies of land, water and plant genetic resources. The question then becomes: Would the new combination of knowledge and natural resources be able to accommodate the demand scenario at acceptable economic and environmental costs?
CHAPTER 8

PRESENT KNOWLEDGE AS A SOURCE OF PRODUCTIVITY GROWTH

Introduction

There are two sources of the higher productivity that will be needed over the next 40 years if the global agricultural system is to meet the demand scenario at generally acceptable economic and environmental costs. One source is known, but not generally used, agricultural technologies and management practices which are more productive than the technologies and practices now in general use. This source of productivity growth is the subject of this chapter. The other source is new technologies and practices embodying new knowledge developed through agricultural research. This source is discussed in the next chapter.

Productivity growth here means more agricultural output per unit of land and water resources employed by farmers. This is a partial productivity concept because it leaves out the labor, energy and other non-land, non-water resources used in agriculture. The rationale for this limited concept of productivity is that we expect land and water to be the most limiting resources in responding to the demand scenario. It is to be understood, however, that other resources, including the knowledge resources discussed in this and the next chapter, must be available on terms such that the economic and environmental costs of increasing land and water productivity are generally acceptable.

What is Presently Unused Knowledge?

In today's world much knowledge about agricultural production is not used because farmers have decided it would not serve their interests. The focus of this chapter is on that part of such knowledge which would increase the productivity of land and water if it were widely used, and which would be widely used if the structure of incentives to which farmers respond were changed appropriately. Two aspects of this formulation need comment. One is to recognize that changing the incentive structure relevant to farmers typically will involve social costs—economic, or political or social, or some combination. For any country at any time, these costs may be judged higher than the benefits in higher land and water productivity that the changed incentives structure would yield. This is to say that some proposals to employ presently unused knowledge more widely will be judged feasible and some will not.

The second aspect is to recognize that the difference between presently unused knowledge (this chapter) and new knowledge (the next chapter) is not clearcut. For example, research over the past decade has demonstrated that, under certain conditions, the acid, infertile soils characteristic of much of the humid tropics can be continuously cropped at a high level of productivity. This is present knowledge which
currently is not widely used. However, it does not appear that the knowledge could
be quickly brought into general use by any acceptable change in farmers' incentive
structure. The literature describing the practices embodying the knowledge suggests
that additional research needs to be done before the economic applicability of the
practices is satisfactorily demonstrated. Accordingly, we consider this an example of
how new knowledge can contribute to increased land productivity and treat it in the
next chapter.

Because the difference between presently unused and new knowledge is fuzzy,
opinions can differ about whether a particular kind of knowledge fits in one category
or the other. This possibility, however, does not diminish the usefulness of the
distinction between the two kinds of knowledge.

Kinds of Presently Unused Knowledge

We refer here to various technologies and management practices for protecting
the productivity of land and water resources against threats of erosion, salinity and
other forms of degradation, and for enhancing their productivity.

Terracing and cultivation techniques that preserve crop residues to reduce the
movement of soil by wind and water and increase filtration of water are examples. So
are the use of irrigation water to flush salts from the soil, and provision of drainage to
avoid waterlogging and salinity.

The important point here about these kinds of techniques is that knowledge of
how to use them and of their costs under many varieties of soil, topographic and
climatic conditions is widely held by farmers, agricultural engineers and agronomists
around the world. The failure to use them more widely where they could protect or
enhance soil and water productivity results, therefore, not from lack of knowledge but
from lack of incentive.

Which Incentives?

The technologies and management practices farmers around the world currently
employ reflect responses to a host of incentives, some provided by markets and some
by government policies. The incentives of interest here are those bearing on
technologies and practices which affect the productivity of land and water resources.
More specifically, we are interested in how those incentives might be changed to
encourage wider adoption of currently known but little used technologies and practices
to increase the productivity of land and water resources at acceptable economic and
environmental costs. More specifically still, we are interested in incentives that induce
farmers to adopt technologies and practices reflecting the full range of the costs of
their operations, including environmental costs, off-farm economic costs, and user
costs. We noted in Chapter 7 that the failure of farmers to take account of off-farm
economic costs and environmental costs was a source of socially inefficient use of
land and water resources. Reducing, if not eliminating this inefficiency would increase the productivity of those resources.

User cost is the loss of future income because of the way resources are used today. For example, the decline in the future value of land because of unchecked erosion today is a user cost of today’s land management practices. Farmers who lack secure property rights in the land they farm would have weak incentives to take account of user costs because they would lack assurance that they would reap the benefits of reducing the costs. Under these circumstances, for example, farmers would tend to underinvest in erosion control because they could not be sure they would receive the benefits of higher future soil productivity. The failure to take account of user costs, therefore, is another source of inefficiency in the management of land and water resources.

Government policies can have a major impact on farmers’ incentives to take full account of all of the costs of their operations. Regulation of pesticides, for example, increases the cost of pesticides to farmers, hence provides incentive to use these materials more sparingly. Whether the result is a socially optimal use of pesticides -- i.e., whether at the margin the social costs and benefits of pesticides are equal -- is, to say the least, debatable. But the effect of the regulatory policy in reducing pesticide use likely is in the right direction.

The effect of policies also can be perverse, e.g., fertilizer subsidies in the absence of environmental protection measures may increase unaccounted-for environmental costs even more than they would be without the subsidy. It has been argued (National Research Council 1989) that in the U.S., crop price and income support programs weaken farmers’ incentives to adopt crop rotational system which would be more environmentally friendly than the current systems because they would rely less on pesticides and inorganic fertilizers.

We make no effort here to deal with the full panoply of incentive changes that might move farmers to adopt widely presently unused technologies and practices that would increase land and water productivity. We focus instead on a set of policies designed to induce farmers to shift toward better land and water management practices by changing allocations of property rights in these resources. As pointed out in the previous chapter, the absence of clear, enforceable property rights is a fundamental cause of the emergence of off-farm economic and environmental costs of agricultural production. As will be shown, lack of property rights is central also to situations in which farmers give too little weight to user costs, i.e., they undervalue the longer run productivity consequences of the way they manage their land and water resources. Thus the property rights issue bears in a major way on the principal concerns of this report. Successful policies to clarify and strengthen property rights in land and water could help to increase the productivity of these resources. The policies would contribute, therefore, to containing the increases in economic and environmental costs entailed by farmers’ responses to the demand scenario.
Why Property Rights are Important

In the context of this paper, the critical feature of a property right in a resource is that it permits the holder of the right to deny access by others to the services provided by the resource except on terms set by the holder. Holders of secure, enforceable property rights in land or water resources can, therefore, be confident that they will capture the value of the services the resources provide, thus giving incentives to protect and enhance their productivity. The less secure and enforceable the property right, the weaker the incentive.

In this line of argument, the absence, or weakness, of secure property rights leads to what Garrett Hardin (1968) called "the tragedy of the commons." Because no one has an exclusive property right in the commonly held resource everyone has equal access to it. Equal access destroys incentives for any individual to conserve the resource or to make productivity-improving investments in it because most of the benefits of this behavior would be captured by others. Thus user costs -- the loss of future income incurred by current use of the resource -- are ignored. The "tragedy" is that under these circumstances, the productivity of the resource eventually is undermined and everyone is worse off than they would have been had user costs been taken into account.

Pingali (1989) cites a substantial body of research in Asia and Africa supporting the argument that secure, enforceable property rights provide incentives to invest in protection and enhancement of resource productivity, and that the absence of these rights discourages such investment. Pingali notes that "successful examples of erosion control investments are generally associated with secure long-term rights to land" (1989, p. 253). In Java a transition from a shifting cultivation system with poorly defined property rights to an agroforestry system with well-defined rights "resulted in high levels of investment for preventing soil erosion" (Pingali 1989, p. 253). And in Vietnam, policy reforms giving long-term land leases to farmers have led to an increase in soil conservation investments.

Systems of Property Rights

There now is a substantial literature addressing issues that arise from the lack of clear property rights in natural resources. It generally is recognized in this literature that the situation Hardin discussed was more characteristic of open-access resources than of common property resources. "Open-access" means literally that access to the resource is open to anyone, and the resource, therefore, is owned by no one. Common property resources are owned by a group, e.g., a tribe or members of a village, and access to these resources is granted only under a set of rules determined either within the group, or in some cases by an external governmental authority.

The global atmosphere is a true open-access resource, at least for the time being, but situations of open-access to land appear rare. The ocean fishery has many features of an open-access resource, despite intergovernmental efforts to regulate its rate of exploitation. Large aquifers in which there is much lateral movement of water
may be exploited as open-access resources. The Ogallala aquifer which underlies much of the Great Plains of the USA often is mistakenly described in these terms. However, because there is little lateral movement of water in much of the Ogallala, it is not a true open-access resource. That is, over much of the region, one farmer's extraction of water from the aquifer does not significantly reduce the supply available to other farmers. Each farmer, therefore, has incentive to take account of the user cost of the current rate of pumping on the individual farm.

Blaikie and Brookfield (1987) note three distinguishing characteristics of common property resources (CPRs):

(a) They are subject to individual use but not individual possession.

(b) They have a number of uses with independent rights of use.

(c) Users constitute a collectivity and have the right to exclude non-members of the collectivity.

Enforcement of the rules of use by members of the collectivity and exclusion of non-members are the critical features of CPR management. The literature referred to above makes it clear that, where this management task is effectively handled, the use of CPRs is not inconsistent with conservation and enhancement of resource productivity. Writing of the Sahelian and Sudanian Zones of West Africa, Gorse and Steeds (1987) state that communal systems of land tenure are widespread and that they are flexible enough to provide incentives for conservation and investment. Within a group occupying a particular tract of rangeland, pasture was "... treated as regulated common property to which all group herds enjoyed access, provided regulations were respected" (Gorse and Steeds 1987, p. 11, emphasis added). The systems were managed by local authorities who made the rules on issues such as land tenure, pasture management and use of woodstock.

Jodha (1987), writing about pre-independence India, states that CPRs in land were of major importance in the state of Rajasthan. Access to the land by villagers was controlled by local feudal chiefs who set the rules of access and use, and charged a fee to users. Out of this arrangement "... there emerged a management system which helped in protection and maintenance of CPRs and regulated their use. The need for revenue rather than ecological concerns created circumstances which insured conservation and regulated use of CPRs" (Jodha 1987, p. 203).

For our purposes here, the important point in this discussion is that communal property rights vested in a system can provide incentives for protecting and enhancing the productivity of the resource, both in the near and longer term. The key is that the property right be clear and enforceable, not that it be communal or private.
Why CPR Systems Break Down

Nonetheless, much concern is expressed in the literature about the effects of CPR management on the productivity of land resources. The concern, however, is not about CPR systems as such but about their tendency to break down under the pressure of population growth, technological change and, in some cases, ill-advised, if well intentioned, government intervention. It is widely recognized that, because CPR systems require communal management, they are vulnerable to the "free rider" problem, i.e., the tendency of some people in cooperative arrangements to shirk their responsibilities in the hope of sharing in the gains of cooperative action without bearing the costs. Rising population density increases the value of individual access to the increasingly scarce land resource, thus strengthening incentives to escape the CPR management constraints. Advances in the technology of land use, especially if combined with increasing access to markets for farm output, further increase incentives of individuals to break loose from the CPR system.

Gorse and Steeds (1987) cite population growth, as well as political and economic changes, as sources of disruption of CPR systems in Africa. Blaikie and Brookfield (1987) also view population growth and increasing commercial opportunities for agricultural output as sources of breakdown in CPR systems, citing Iran under the Shah and the Ngwakelse District of Botswana as examples. Increasing commercialization creates opportunities and incentives for village or district "big men" to "...use the law, deceit or strong arm tactics to acquire rights on the commons themselves... Less powerful groups, hitherto content to 'stint' in the belief that others will do the same, are more tempted to free-ride" (Blaikie and Brookfield 1987, p. 193).

Government interventions also have tended to weaken CPR systems in a number of countries. The typical result has been to substitute more central control for local control of the systems. Gorse and Steeds (1987, p. 192) write that "the removal of responsibility of management from the community... to bureaucratic decree has frequently been disastrous... The nationalization of forests in Nepal between 1957 and 1961 had such an effect when villagers feared that the government's new powers in taking over the forest would lead to the timber being auctioned off to logging contractors." Jodha (1987) asserts that land reform in India, by breaking up the control of land by local authorities, had a similar effect in weakening CPR systems in Rajasthan.

Substitutes for CPR Systems

The breakdown in CPR systems, if the systems are not replaced by some other assuring clear and enforceable property rights, can lead to open-access exploitation of the land resource. Something like this evidently happened in Rajasthan (Jodha 1987) and Nepal (Gorse and Steeds 1987). But there is much evidence of transitions from CPR systems of property rights to systems of private rights which result in the kind of resource-conserving practices expected where rights to the resource are secure. Pingali (1989) warns against simplistic distinctions between pure communal property rights and pure private rights, noting that there is a complex continuum of forms
between the two. Nonetheless, he cites a substantial body of research in Africa and Asia supporting the argument that population growth and technological change set up pressures for a transition from land-extensive systems of common property rights to land-intensive systems of private rights. The transition does not always occur smoothly and, in some instances, it has not occurred at all. Pingali (1989) cites Tanzania and Vietnam in the 1970s as cases where socialist systems of property rights eliminated the tendency toward privatization. Nonetheless, the transition from CPR systems of rights to private systems has occurred often enough to describe it as a "basic tendency" (Pingali 1989, p. 249).

Migot-Adholla et al. (1991) found the transition from CPR systems of land rights to private systems to be characteristic of the evolution of property rights in land in Sub-Saharan Africa. Like Pingali, Migot-Adholla et al. view systems of land property rights in Africa as lying along a continuum, with CPR systems at one end and private systems at the other. They note that the CPR systems in Sub-Saharan Africa were consistent with conserving uses of the land under the conditions of relative land abundance characteristic of that part of the world, at least until recently. Like other students of these issues, Migot-Adholla et al. attribute the transition of CPR systems to private systems in Sub-Saharan Africa to rising population, technological change in uses of land and increasing commercialization of agriculture. They find support for this argument in a statistical analysis of the relationships between population density, degree of commercialization of agriculture, land productivity, and systems of property rights in land in Ghana, Botswana and Kenya.

Migot-Adholla et al. found no consistent relationship between systems of land property rights and investments in land improvements. They found that such investments were positively related to greater private control of land in parts of the regions they studied, but not in others. Neither did they find a consistent relationship between systems of property rights and land productivity. Of this latter finding they note that it "...undermines the conventional view that land rights are a constraint on productivity." (They presumably mean traditional, or CPR systems of rights). Citing work by Boserup (1981) and Pingali et al. (1987), they go on to conclude that technological advance and agricultural productivity under any system of land property rights likely would be constrained in the absence of "... accompanying improvements in infrastructure, rural health and education, and price incentives..." (Migot-Adholla et al. 1991, p. 172).

Reflections on the Property Rights Issue

This discussion of property rights in land suggests several conclusions of special interest to this paper. If CPR systems of land rights are consistent with conserving uses of the land, and if, in the absence of government interventions, the processes of agricultural intensification underway all through the less-developed world will induce a transition to private systems of land rights, then it would seem to follow that user costs, by and large, are now and will continue to be reflected in farmers' land management decisions. So far as user costs are concerned, present knowledge about land management already is, and will continue to be, employed in a way approximating
socially optimal use. In this case, the incentive signals sent by the structure of land rights are on target. The implication is that little if any increase in land productivity can be achieved by changing the structure of rights. On the contrary, any change likely would be counterproductive.

This is a comforting conclusion because it indicates that user costs of land management are largely not a problem. The limited policy resources of LDC governments and the international community concerned with agricultural development can be devoted to more pressing problems.

The conclusion is only mildly comforting, however, for several reasons. It deals only with user costs of land management. It has no bearing on off-farm economic costs or on environmental costs. For example, population growth in LDCs and present tenancy systems are tending to promote smaller and more fragmented landholdings which could increase off-farm economic costs, e.g., sediment from farmer A’s land reduces crop production on farmer B’s land. Similarly, the fact that user costs are taken into account is consistent with rising environmental costs of pesticide damages to human health or wildlife, downstream sediment damages, and losses of biological diversity from deforestation. Nor does the conclusion about user costs of land have any bearing on the effects of property rights in water on farmers’ incentives to use irrigation water more productively.

In principle, there is, for any country, some structure of property rights in land and water which would give farmers and other managers of these resources incentive to take proper account not only of the user costs of land management but also of off-farm economic costs and environmental costs. There is no scope in this paper to explore what these structures of rights might look like. Two observations are relevant, however. One is that, until much more is known about the environmental costs of agriculture in LDCs, it will be impossible to judge accurately the benefits to be gained by investing in a new structure of property rights to reduce the costs. The second observation stems from Postel’s (1989) estimate that about 25 percent of the world’s irrigated land is "affected" by salinity and waterlogging. If Postel is right, then changing the structure of property rights to induce farmers, and irrigation managers, to adopt presently known techniques to reduce these off-farm costs would contribute relatively little to the productivity gains that will be needed to meet the 2030 demand scenario at acceptable economic and environmental costs. This is not to say that these property rights changes are not worth doing. They probably are on both economic and environmental grounds. The point is that the resulting productivity gains likely would be small relative to the increased production implicit in the demand scenario.

Conclusion

The gains in productivity of land and water that might be achieved through wider use of presently known techniques and practices are uncertain. The discussion of the effects of land property rights on user costs suggests that little would be gained by reducing these costs because they probably already approximate a social optimum.
Postel’s evidence on the extent of irrigation-related salinity and waterlogging suggests that wider use of present knowledge could increase land and water productivity, but that the contribution would be small relative to that needed to meet the demand scenario. Although little is known about environmental costs, they almost surely are sufficiently high that reducing them would contribute to higher land and water productivity. How much that contribution might be, however, is quite uncertain.

We conclude that wider adoption of present knowledge would contribute something to the increases in land and water productivity that will be needed over the period to 2030. Although the amount of the contribution cannot be accurately estimated, we believe it would be less than is commonly believed. The reason is that much of the literature on resource degradation in LDCs suggests that user costs of land management are substantially greater than is socially optimal, implying large productivity gains from reducing the costs. Our discussion of the property rights issue suggests that this view is mistaken. The productivity gains expected from reducing user costs in this case would prove illusory.

If this assessment is correct, then most of the productivity increases needed to meet the 2030 demand scenario at acceptable costs will have to come from new knowledge that farmers can apply. How this might be done is discussed in the next chapter.
CHAPTER 9

NEW KNOWLEDGE AS A SOURCE OF PRODUCTIVITY GROWTH

Introduction

The preceding discussion indicates that, within the existing knowledge regime, the supplies of the resources considered would be inadequate to accommodate a doubling in global demands for food and fiber, except at sharply higher economic and environmental costs. Institutional improvements, e.g., establishment of clear and enforceable property rights in land and water resources, would increase the productivity of land and water resources somewhat, but would not basically change the prospect for rising economic and environmental costs, given the demand scenario. In that scenario, the only way higher costs can be avoided is to increase knowledge about agricultural production practices by investing in the people working in agriculture and in the technical and institutional innovations they will need to increase the productivity of all their resources.

This argument for investing in knowledge rests on two propositions:

(a) that across a wide range of situations the elasticity of substitution of knowledge for other resources is high; and

(b) that the elasticity of the supply of knowledge relevant to natural resource management is high relative to the elasticity of supply of natural resources.

Put differently, the second proposition is that a dollar invested in increased knowledge about management of agricultural resources will return more in net social product from agriculture than a dollar invested in expanding the supply of natural resources within the existing knowledge regime.

No effort is made here to demonstrate the validity of the two propositions, beyond noting that they are consistent with the experience of global agriculture over the past 40 or 50 years. That experience was characterized by an unprecedented increase in global agricultural output accompanied by a massive expansion of knowledge embedded in people, technology and institutions and, by comparison, a modest expansion in the quantities of land and water devoted to agricultural production. The supply of plant and animal genetic resources may possibly have diminished a little, while there is no evidence that the climatic resources for agriculture have changed over these few decades.

The discussion in this chapter is focused on the conditions necessary to expand knowledge pertinent to agricultural production on the requisite scale, at the requisite time and of the requisite sort. Most attention is given to increasing knowledge
embedded in technology and management practices, not because human capital and institutions are less important, but because the processes for directly developing new technology and management practices are in the "front line" of the technological battle. They depend, of course, on institutional effectiveness and, especially in the longer term, on human capital of the requisite quality. The roles of both education and institution-building in development are crucial.

The Importance of Yield-Increasing Technology

The chapters dealing with natural resource supplies have indicated that the land constraint likely will be tightest in Asia and the water constraint tightest in Africa. Even in Asia, however, the potential for increased irrigation over the next 40 years appears to be substantially less than it was over the past 40. The implication is that Asia will need new technologies to increase yield on both irrigated and rainfed land. The imperative to increase yields per unit of land is less strong in Africa and Latin America but, in those regions also, the majority of all future increases in crop production will probably have to come from higher output per hectare. We now review, in turn, the prospects for the major groups of cereals.

Rice

Rice is predominantly an Asian phenomenon, and is expected to remain so into the foreseeable future. Asia currently accounts for roughly 90 percent of global production and consumption of rice, and the International Economics Department of the World Bank (1990) expects this to hold also into the next century. Future increases in rice production, therefore, will depend overwhelmingly on increasing production in Asia.

Although the total amount of land in crops in Asia is not likely to increase much over the next several decades, the amount of land in any single crop may vary, depending on the changing economic attractiveness of various crops. Should rice become more profitable relative to other crops, land in rice might increase, easing the burden on yield increases to accommodate the higher demand. We assume here, however, that the land constraint in Asia will be such that land in rice will remain virtually constant at early 1990s amounts. In this case, the entire demand growth over the period to 2030 will have to be met by increasing yields.

How much of an increase is that? In the International Economics Department's (1990) projection, rice consumption in Asia, and in the LDCs as a whole, increases 2.4 percent annually over the period 1988/89-2005. On the assumption of no change in the amount of land in rice, 2.4 percent is the required annual rate of yield increase over that period.

In the global demand scenario for 2030, we projected an aggregate for all grains, not distinguishing among wheat, coarse grains and rice. The projections implied an average annual increase in global grain consumption of 2.3 percent over
However, we made an argument that rice consumption likely would grow less than the average, and coarse grain consumption more. Specifically, we assumed that, over 2005-2030, rice consumption in the LDCs would grow with population as projected by the United Nations (1989), namely 1.3 percent per year. In making the argument for the changing pattern of demand growth for rice and coarse grains, we drew on recent experience in Asian countries, such as Korea, where, with rising per capita income, the income elasticity of demand for rice has fallen sharply and the comparable elasticity for coarse grains has risen, reflecting increasing per capita demand for animal products (Ingco 1990).

The question for rice technology therefore is: Can yield increases of 2.4 percent and 1.3 percent be achieved, respectively, in 1988/89-2005 and 2005-30 at economic and environmental costs that Asian societies would find acceptable? Experience in the 1980s suggests a cautiously optimistic answer to the question. Global rice yields increased 2.4 percent annually from 1978/82-1985/89 and production rose 11 percent (US Department of Agriculture 1990). This must largely reflect Asian experience, given that region’s dominance in world rice production. In the same period, real rice prices declined (International Economics Department 1990). The combination of lower prices and higher output implies that the rice economy of Asia contributed substantially to higher economic welfare of Asian people in the 1980s. This conclusion, in its unqualified form, ignores, however, possible negative income distribution effects on the welfare of some social groups.

Earlier, it was noted that consumption of nitrogen fertilizers in Asia increased from 19.5 Mt in 1979/80 to 33.4 Mt in 1988/89. Much of this increase was surely applied to rice land. It also was noted that use of pesticides in Asia increased sharply in the 1980s, and much of this also must have been applied to rice. No firm conclusion was reached about the environmental costs of these increases in intensity of use of fertilizer and pesticides in Asia, except that the costs doubtless rose. How important higher environmental costs may have been relative to the unmistakably lower economic costs of rice production is yet unknown but is being actively investigated at IRRI and elsewhere.

The yield and economic cost experiences of Asian rice production in the 1980s support a judgment that the region can increase rice yields and production over the next several decades at the requisite rates and on socially acceptable terms, bearing in mind the uncertainty about recent and possible future environmental costs. This judgment needs further consideration, however, because there now is widespread concern among rice specialists that the recent generally favorable yield experience may not be sustainable. The concern is based on evidence of growing environmental difficulties and stagnant or even declining yields in some areas of Asia (e.g., Pingali 1991) and, more basically, on the fact that the yield potential of rice varieties has not increased since the 1960s, when IRRI released the first modern varieties for general use (Ruttan 1991; Pingali 1991). The rapid increases in rice yield since the 1960s were achieved by exploiting that initial potential, which, in turn, came mainly through increasing the rice harvest index, i.e., the ratio of grain to total plant biomass.
Average global rice yields in 1985/89 were 3.3 t/ha (US Department of Agriculture 1990) only about one-half the 6.5 t/ha or so contemporary yield potential (Pingali 1991). Potential yields are those achieved on experimental plots under controlled conditions, and average yields on farmers' fields will never equal potential. Nevertheless, the present gap between average and potential yields offers some promise of continued increases in average yields. More specifically, if average yields grow at 2.4 percent over 1988/89-2005, the rate of consumption increase projected by the World Bank's International Economics Department over that period, then yields in 2005 will be 4.9 t/ha, roughly three-fourths of present yield potential. Achieving this yield growth would doubtless require more intensive application of fertilizer and probably also of other inputs, and more efficient use of irrigation water. But these conditions do not appear out of reach for Asian rice producers over the next 10-15 years (Anderson and Herdt 1989). Over the longer term -- say the period 2005-30 -- continued increases in rice yields will surely be eased through some increase in yield potential from present levels.

Rice and biotechnology. What are the prospects for developing new technologies and management practices that would increase potential rice yields? The discussion of this question now revolves significantly around the possibility of breakthroughs in biotechnology. Anderson and Herdt (1989) judge biotechnology to have large potential for agriculture, but that its impact in LDCs likely will be insignificant until beyond 2000. They also note that the Rockefeller Foundation is funding biotechnological research on rice, which focuses on increased plant resistance to insects and diseases and on biological insecticides. Anderson and Herdt (1989, p.690) judge these prospects as "relatively bright." One aspect of these technologies not especially emphasized is that, if successful, the technologies should be not only economically attractive to farmers but environmentally beneficial as well.

Ruttan (1991) doubts that biotechnology will contribute measurably to plant productivity over the next couple of decades, putting him among the sceptics with regard to biotechnology's near-to-medium term potential. Others are more optimistic. Kenney and Buttel (1985 p.86), citing research results in both public institutions and private firms, concluded that "The impact of biotechnology on agriculture over the next twenty years will likely be staggering ...." After surveying published biotechnological research on improved weed control and resistance to insects and diseases, Gasser and Fraley (1989, p. 1295) concluded that "genetically engineered soybean, cotton, rice, corn, oiseed rape, sugarbeet, tomato and alfalfa crops are expected to enter the market place between 1993 and 2000." Using the delphi method, Gotsch and Rieder (1989) collected and summarized opinions about the future of biotechnology of experts in genetics and molecular biology, plant breeding, plant physiology, agricultural product research and development, and commercial aspects of agriculture.

A main conclusion of Gotsch and Rieder was that, over the next decade or so, biotechnology would supplement, not replace, conventional crop breeding, and that its major contribution would be to shorten the breeding period for new varieties. Plant improvements involving manipulation of a single gene were expected to be available before 2000. Improvements involving several genes, such as tolerance to cold and drought or nitrogen fixation by non-legumes, were not expected to be available until
well after 2000. In an analysis of the technical and economic potential of agricultural biotechnology, Kalter and Tauer (1987, p.424) concluded that: "Scattered evidence regarding the probable economic impacts of biotechnology for agriculture suggests at least a continuation of the sustained productivity improvements achieved over the last fifty years with a possible acceleration in the rate of productivity gain (particularly in select sectors)."

Three characteristics of the future situation appear to be particularly challenging: (a) The importance of achieving breakthroughs in rice yield potential in the first or second decades of the next century; (b) achieving such advances and related yield-increasing technologies, with acceptable economic and environmental costs; (c) to the extent that these technologies are reliant on irrigation water, improving practices to manage irrigation water more efficiently. The first challenge has already been discussed. The second, particularly that part involving environmental costs, deserves emphasis because these costs now are perceived to be of increasing importance. The third challenge simply reflects the prospect of increasing scarcity of irrigation water in Asia.

Meeting the three challenges will require that Asian agricultural research institutions, including IRRI, have a clear and broad perspective on the longer term problems facing the Asian rice economy and that they receive financial support from the international donor community and from Asian governments sufficient to do the job. Recent experience in this regard is mixed and is anything but uniform across Asia (Pardey, Roseboom and Anderson 1991, pp. 226-43, p. 416), although it must be observed that most Asian governments have done better than their counterparts in other regions in protecting and sustaining their research infrastructure. At the international level too there is cause for concern. Much of the relevant external assistance with research resources is funneled through the CGIAR system, which, as Gryseels and Anderson (1991, pp. 320-1) note, devotes only about 17 percent of its effort to rice per se, with some 63 percent of this directed to Asia. These observers go on (p. 323) to hypothesize that the CGIAR system has "gone overboard" on Sub-Saharan Africa, perhaps to Asia's ultimate cost.

Wheat and Coarse Grains

Unlike rice, production and consumption of wheat and coarse grains are widely scattered all around the world, in both more-and LDCs. Although some regional shifts in production of these crops are likely over the next several decades, especially when account is taken of possible changes in regional climates, and of the probability of agricultural reforms in the CIS, production and consumption of the crops are not likely to be less geographically dispersed than they are now. All this has several implications for thinking about the role of new technologies in production of these crops. One is that the imperative need to increase yields seems less pressing for these crops than for rice. The relative abundance of land in Africa, Latin America and North America, where these crops presently are grown in significant amounts, suggests this. Consequently, although most of the increase in global wheat and coarse grain production over the next several decades likely will come from yield increases, some
can be expected to come also from expanding land in these crops. In fact, if our projection of a significant increase in LDC cropland by 2030 materializes, most of it likely will be in wheat and coarse grains in Africa and Latin America.

The second technology-relevant implication of the geographic dispersion of wheat and coarse grain production is that opportunities for trade in these commodities among major world regions are much greater than for rice. Consequently the pressure on any particular country, or region, to meet rising demand for wheat and coarse grains by increasing its own production may be less than it apparently is in Asia with respect to rice. The importance of developing higher yielding technologies for wheat and coarse grains is undiminished, but the advances could be concentrated in a relatively few countries and the benefits transmitted to others through trade.

This argument suggests that, in principle, there is no particular reason to focus only on the less-developed world in considering the prospects for developing higher yielding technologies for wheat and coarse grain production. In fact, however, there are powerful reasons for an LDC focus. The demand scenario indicated that over 90 percent of the increased global demand for grain over the next several decades will be in these countries. Their labor and natural resource endowments suggest that it would, in many cases, make economic sense for them to satisfy much of the demand increase themselves, rather than seek to expand non-agricultural exports and use the proceeds to import wheat and coarse grains. Of course, some countries will conclude that the import option would best serve their economic interests and probably most countries would rely to some extent on imports. Nonetheless, a strictly economic calculation would indicate to many nations that they should meet much of the rising demand for wheat and coarse grains by expanding domestic production, and that they should seek the yield-increasing technologies that would permit them to do this. Beyond economics, political pressures in many countries to increase food self-reliance would, as for rice, reinforce the economic argument for increased domestic production of wheat and coarse grains.

Because of the importance of increasing production of these commodities in the LDCs, the discussion here of finding higher-yielding wheat and coarse grain technologies is focused on the less-developed world. This is not to say that continued technological advance in these commodities in the MDCs is unimportant. It is important, not least because their advances, with proper adaptations, will usually be serviceable in the LDCs also. Moreover, over the next several decades many presently LDCs, despite their best efforts to increase domestic production, will at some time need wheat and coarse grain imports. But the agricultural research and development capacity of North America, Western Europe and Japan, for example, is strong and, presently at least, seems able to take care of itself. The critical issues are in the less-developed world.

Livestock and demands for animal feed. With a total consumption of probably some 600 Mt (Avery 1991, p. 64), livestock is an important consumer of cereal grains. In this area, technology could also make a substantial contribution to improve the efficiency of future use, especially for pigs and poultry. Present feed conversion (kg fed
per kg of liveweight gain produced) in the less-developed world is high. First, most feeds in the developed world are highly deficient in the amount and quality of protein they provide, which forces animals to excessive consumption of the carbohydrate-rich ingredients (i.e., cereals) to satisfy overall needs. For example, in China an estimated 100 Mt of cereal feed is presently being used to produce 15 Mt of pork, representing a feed conversion of about 7:1. With an optimal protein/energy balance, a conversion of 4.7:1 is possible, which if achieved would allow for a saving of more than 30 Mt of feedgrain (World Bank 1987). Similarly, a saving of 10 Mt of feedgrain could be expected in Eastern Europe, if proper protein/energy balances were used in the pig and poultry feed (de Haan, Schillhorn van Veen and Brooks 1992). To overcome such imbalances, technology generation will be essential to develop more efficient high-protein crops, to eliminate toxic substances from protein-rich agro-byproducts such as cotton- and rape-seed cakes, and to identify more effective production processes for synthetic amino-acids to be able to lower optimal protein levels. Second, pig breeds in the developing world are still mainly of the lard type, accumulating large amounts of energy-expensive fat. The progressive replacement of these traditional breeds by leaner types of animals will reduce the feed conversion further. For example, in China, the feed conversion could fall from 4.7:1 to 4:1 through the change to leaner breeds, or an additional saving of 10 Mt of feed (World Bank 1987). Third, substantial savings are also possible through a shift from cereals to cassava in animal feed.

Wheat. Over the past couple of decades, technological advance in LDC wheat production, as measured by the rate of yield increase, has been remarkable, no doubt reflecting in part the fact that the modern wheat varieties are particularly well suited to irrigated production -- some 42 percent of LDC wheat area (CIMMYT 1989a, p.2). The achievement in yield performance suggests a well-developed capacity to develop higher yielding varieties of wheat.

In expressing this optimistic judgment, we should note that at least some of the people who actually do the work are less optimistic than ourselves. For instance, in projecting growth rates and the component effects of these for wheat through to 2000, CIMMYT (1989a) sees the varietal component for the rate of gain of only 0.7 percent per year in its most "optimistic," and down to 0.4 percent per year in the most "realistic" projection. The combined effects of irrigation, varietal improvement and added fertilizer effects for these two projections are 2.3 and 1.5 percent, respectively. These seem to us to be rather cautious, especially in view of the past achievements in yield advance. In subsequent, yet unpublished, forecasts CIMMYT staff are even more guarded in their "pessimistic realism" and consider that the rate of increase in wheat production will be even slower over the next couple of decades than the past. The expected slowdown is based on the rigidities of the US Conservation Reserve Program, the rise in the Green Movement in Europe with increasing restrictions on the use of agricultural chemicals, and the recent negative trends in total cereal area in China and India.

In assessing how to meet the wheat demand challenge for our two projection periods, we feel that a midway (i.e., between CIMMYT’s optimistic and realistic) combined yield contribution of 1.9 percent per year should be achievable, which leaves an increased area-sown contribution of 1.1 and 0.4 percent per year as the residual
component. Given the land availability assessment of Chapters 3 and 7, this should be readily achievable, especially in South America under the right incentive structure. The more difficult period would seem to be in the first period to 2005, bearing in mind that CIMMYT (1989a) assesses the area contribution to growth of wheat production to 2000 at only 0.7 percent per year.

Implicit in our relatively optimistic long-term view is a judgment that there will be considerable contribution both from biotechnology-based innovations and through improved crop management as farmers become more skilled in realizing the potential that already exists for wheat-yield improvement. Needless to say, all such advances depend crucially on the sustained and strong support for investments in national and international research and extension systems. This naturally also includes institutional reform issues, so that wheat research programs in the many affected countries can be more effective in advancing pertinent and productive knowledge. Other CGIAR institutions, such as ISNAR (for institutional improvement), IFPRI (for policy reform) and IIMI (for enhanced irrigation management), for instance, will also play important roles in these "big-cast" processes.

In spite of the noted importance of irrigation in many LDC wheat industries, much wheat is still grown under dryland conditions. Many of these dryland areas feature some of the same challenges faced by people working on crop improvement of the coarse grains that are noted below.

**Coarse Grains.** One reason for giving explicit attention here to coarse grains is that the demand scenario indicates a faster rate of increase in global demand for coarse grains over the period to 2030 than for wheat. This pattern is based heavily on Asian experience showing that, with rising per capita income and urbanization, demand for coarse grains as animal feed grows relative to demand for wheat and rice. The demand scenario assumes that this pattern will be increasingly evident not only in Asia but in Latin America and Africa as well.

The faster expected growth in LDC demand for coarse grains and the so far slower rate of advance in coarse-grain technology suggest that, in considering prospects for developing higher yielding technologies, due attention must be given coarse grains. Most coarse grain production in LDCs is under rainfed conditions, although comprehensive data are lacking. A report by the India Department of the World Bank (1991b) indicated that, in 1986, four percent of the sorghum grown in India and five percent of the pearl millet were under irrigation. The percentage of maize area irrigated is reported (personal communication from D. R. Byerlee, CIMMYT) as 17 percent and may well increase relative to other coarse grains. Maize, sorghum, and millet are overwhelmingly the principal coarse grains in most LDCs.

Yields of coarse grains generally have not increased as rapidly as wheat yields in the LDCs over the past few decades. In India, for example, the World Bank (1991b) reported average annual percentage increases in yields over 1960/61-1986/87 for maize, sorghum and pearl millet of 1.5, 0.9, and 1.3, respectively. Most disturbingly, yield growth rate of LDC maize fell from 2.8 in the 1970s to 1.4 percent in the 1980s (CIMMYT 1991, p. 23).
Why have LDC yields of coarse grains not generally increased as rapidly as those for rice and wheat, particularly in the 1980s? The answer is not obvious, but it clearly has something to do with the fact that coarse grains have benefited far less from the spread of irrigation than have rice and wheat. This is no accident. In Asia rice is the dominant lowland crop, coarse grains generally being grown in the uplands, where irrigation typically is not economically feasible. Moreover, the modern wheat varieties developed by CIMMYT, its predecessors and national collaborators were particularly productive under irrigated conditions, and were often further adapted for these conditions by national agricultural research institutions particularly those in Mexico, India, Pakistan, and parts of the Middle East. In Sub-Saharan Africa, where coarse grains are an important crop, irrigation development has lagged.

Maize. Anderson, Herdt and Scobie (1988, p.24) offered some explanations as to why research on maize has had less success than research on rice and wheat. One is that maize is grown under highly diverse conditions, so that individual varieties have to be adapted to narrow circumstances. By contrast, lowland rice and irrigated wheat are grown under much more homogeneous natural conditions. A related reason is that maize is grown all around the less-developed world unlike much rice, mostly an Asian crop, and most wheat, which, among the LDCs, is grown mainly in West Asia, the Middle East and North Africa. A consequence of the greater geographical dispersion of maize production is that international maize researchers have had to establish and maintain effective working relationships with a large number of national agricultural research institutions that are diverse in needs and situation, yet often slender in resources compared with many of those focused on wheat and rice. The maize research establishment thus is in some senses inherently more cumbersome and difficult to manage than that for wheat and rice.

Duvick (1991, p.46) observed that maize yields in the LDCs have not increased as fast as those of rice and wheat, and noted that, in many countries, maize is either the second or third crop of choice or is grown in areas with many environmental constraints. In either case, farmers find use of fertilizer and other inputs on maize economically unattractive relative to the typical situation with rice and wheat in much of the world and absolutely so, as in the case of the smallholder sectors of many African nations (Anderson 1991).

Speculating about new maize technologies for the 1990s, Duvick (1991) expects that maize hybrids will spread ever more widely in LDCs. This assumes that the marketing infrastructure for both production and inputs will be adequate, and that the market for maize continues to expand. If our demand scenario is reasonably on target, this market condition would be met. Duvick sees demand by farmers for a stream of yield-increasing hybrids as providing a strong incentive to breeders -- public and private -- to do the necessary research and development.

Researchers will not have an easy task if LDCs are to succeed in meeting future demands for coarse grains at acceptable economic and environmental costs. Recall that, in the demand scenario, LDC consumption of coarse grains grows 2.2 percent annually over 1988/89-2005 and 3.2 percent annually over 2005-30. Some of the increase over the 40-odd year period -- perhaps one percent per year -- could probably
be met by bringing more land under coarse grains in Africa and Latin America, but most of the burden, particularly after 2005, will have to be borne by rising yields.

The situation is somewhat different amongst the coarse grains, given that they tend to fit into rather different ecological niches. Accordingly, we first briefly consider the situation for maize, the subject of this subsection, before turning to those for sorghum and millet. CIMMYT (1989b, p.42) considers that a rate of genetic gain in maize yields of 1.5 percent per year is achievable. Given the complexity of the other factors that contribute to enhancing maize yields, CIMMYT is perhaps wise to avoid, and certainly can be forgiven for dodging, quantification of the contribution of other factors to changing maize yields in the medium to long term. In considering how to meet the coarse-grains demand challenge as a whole over our two forecast periods, we first assume that the lion's share of the additions will come from maize. Notwithstanding the slow progress of the 1980s, we feel that a varietal component of yield gain of 1 percent per year is surely achievable and an improved crop-management component of another 1 percent should also be manageable. Such progress would leave only a small area contribution to production growth in the first projection period but a rather more challenging role for area increases in the second.

The multitude of factors that bear on success in maize production has been effectively described by CIMMYT (1990), especially for the complex and varying country situations in Sub-Saharan Africa. These factors range over marketing problems, environmental hazards, shortages in services that contribute to productivity such as draft power, and the policy environment generally. Certainly, with a favorable conjunction of such factors, productivity increases in maize will indeed prove to be remarkably high. The difficulty in long-term forecasting is to assess the possibilities of such a conjunction of favorable developments.

The several assumptions concerning area-growth contributions to overall change in production of rice, wheat and maize are brought together in Table 9.1. These data link back to Table 3.1, but in Table 9.1, maize is reported separately from other coarse grains, using data from CIMMYT (1990). The implied constant annual growth rates in additional crop area for these three crops from the base period to 2030 is 0.57 percent, which does sit comfortably within the assumed contribution of new cropland potential summarized in Table 7.2. The key missing elements from our purview here are the two other coarse grains of major importance in LDCs, namely, sorghum and millet, to which attention is now briefly turned.

**Sorghum and Millet.** Sorghum and millet will find it hard to contribute their "share" to the speculated growth of coarse grain yields. This is especially so in the case of millet, which grows in the least-favorable environments in those LDCs where it is most important. Crop improvement programs have continued to raise potential yields of these crops and very high yields are achievable under favorable circumstances. The problem is that favorable seasons are the exception and most of the time these crops must endure very dry conditions that do not result in significant increases in yield or intensive application of inputs that might help boost yields. In other areas, the value of the grains is insufficient to warrant more intensive crop management, in spite of the wide spread of improved varieties and hybrids of both these crops.
Crop improvement work in Africa has been much less successful than in South Asia, and farmers have not yet been presented with the option to use varietal materials that are significantly better than the locally adapted ones. Such considerations led Anderson and Herdt (1989) to be relatively pessimistic about the prospects for yield advance in most sorghum and millet areas. If progress is to be made that contributes to significant rates of yield increase, it will have to be as a result of a long and sustained research endeavor, particularly focused on improved natural resource management, especially of soil structure and fertility. Such work is slow and "investors" must exercise patience while sustaining a long-run commitment of research resources.

We choose not to be explicit about how sorghum and millet will contribute to the scenario demands for coarse grains. In general terms they will likely follow the maize contribution but be smaller and slower. There does seem to be adequate land at the extensive margin to provide the needed area component of growth, even if yield gains should prove illusory. Since both area and yield gains will depend so crucially on better crop management, it is to this topic that we turn momentarily.

Table 9.1: Overview of Cropped Area Contributions to the Growth of Three Major Cereals

<table>
<thead>
<tr>
<th>Cereal</th>
<th>Base period area ca. 1985 (million ha)</th>
<th>Area growth rate* (%) to 2005</th>
<th>Projected area (million ha)</th>
<th>Area growth rate* (%) to 2030</th>
<th>Projected area (million ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>145</td>
<td>0.0</td>
<td>145</td>
<td>0.0</td>
<td>145</td>
</tr>
<tr>
<td>Wheat</td>
<td>225</td>
<td>1.1</td>
<td>280</td>
<td>0.4</td>
<td>309</td>
</tr>
<tr>
<td>Maize</td>
<td>125</td>
<td>0.2</td>
<td>130</td>
<td>1.4</td>
<td>184</td>
</tr>
<tr>
<td>Total</td>
<td>495</td>
<td>0.6</td>
<td>555</td>
<td>0.6</td>
<td>638</td>
</tr>
</tbody>
</table>

* Assumed constant percent per year.
Roots and Tubers. Finally, one last word on roots and tubers and the prospects for future increases in their production (Horton 1988). While a number of international agricultural research centers (notably CIP, CIAT and IITA) have mounted strong research programs on improvement of potatoes, and to a lesser extent of sweet potatoes and cassava, any significant improvement both in the yields as well as the dissemination of the yield-improving technologies must come from a strengthening of the national research and extension services. As with the cereal crops, more attention needs to be addressed to varietal distribution and the adaptability of these varieties to various agroclimatic conditions. The transfer of technologies appropriate to the special storage and transport problems of these crops (their rapid perishability and bulk, for example), combined with technologies enabling local processing to branch out into a greater variety of derived products, will also help in the substitution of noncereal crops for cereals in consumption. Just as importantly, however, to the ultimate survival of these crops as economically and nutritionally viable alternatives to cereals, will be the strengthening of coordinated, rational policies that afford these crops the chance to compete with cereals "fairly" and without disincentives on domestic markets.

Farming-Systems Resource-Management Approaches

The research described in the preceding section is designed to increase yields by developing improved cultivars of plants -- the kind of research that was fundamental in the Green Revolution in wheat and rice production. There is a role also for research designed to achieve yield increases by modifying the physical environment in which plants grow. This latter kind of research can be called farming systems research because it focuses on the farm operation as a whole. According to Anderson, Herdt and Scobie (1988, p.41)

"Farming systems research is the attempt to understand and devise improvements for the overall operation of farms...Basic to this type of research is an appreciation of the farm as a system in which the farmer and the farm household are integral parts. The farming system is the arrangement of farming activities within the physical, biological and socioeconomic environment in accordance with a farm household’s goals, preferences and resources. Every farming system is part of larger systems (for example, the local community) and can be divided into subsystems (for example, cropping systems)."

Farming systems research (FSR) covers an enormous range of farming and research activities including work that is increasingly designated as resource management research (RMR). We offer three illustrative examples of research that are especially appropriate for addressing coarse-grain yields under rainfed conditions. One concerns measures to increase conservation of soil moisture. The second describes research done at ICRISAT to improve the productivity of farming deep black soils in the wetter areas of semi-arid India; and the third describes research designed to increase yields on the acid infertile soils that characterize much of the tropics.
FSR and Conserving Soil Moisture

All technologies and management practices to conserve soil moisture are aimed, one way or another, at controlling runoff and evaporation of water and transpiration by weeds (Papendick and Campbell 1988). Conservation of soil moisture favors higher yields not only by reducing plant water stress, but also by increasing the yield response to fertilizer. Deuson and Sanders (1888, p.611) note, for example, that in areas of the Sahel where annual precipitation averages less than 800 mm, increased soil moisture combined with "moderate fertilizer levels results in large and consistent increases of sorghum yields." Sanders has also made the point (as noted in Ruttan 1989, p.68) that, in parts of the Sahel, "It has been documented that with water conservation techniques of various types, the whole picture regarding returns to fertilization is changing. The combination of these two technologies, as demonstrated in farm-level trials, has both a very high economic return and a reduction of risk."

Techniques for reducing runoff and evaporation are diverse, but often are put in two classes, those involving "engineering", e.g., construction of terraces or bunds, and those involving farm management practices such as mulching with crop residues on the soil surface. Although terraces often are constructed to reduce soil erosion, their land leveling effect also conserves soil water by reducing runoff and increasing infiltration.

Yudelman and Hillel (1988) assert that, in India and elsewhere in the less-developed world, engineering approaches to soil moisture conservation have proved uneconomical for many farmers. As a consequence, researchers, and at least some farmers, have turned to alternative techniques to conserve soil moisture (Greenfield 1988, p. 146). Low-tillage, or minimum-tillage techniques that leave much of the previous crops' residue on the soil surface as mulch and leave the soil in rougher aggregates than conventional tillage are being investigated, and adopted by some farmers (Yudelman and Hillel 1988).

Unger (1988) notes that the water-conservation effect of crop residues can be substantial only if the amount of residue exceeds 2 t/ha. In dryland areas the amount of residue with winter wheat, grain sorghum, cotton and millet is, however, often less than 2 t/ha. Unger also observes that, although residue will almost always reduce runoff, its evaporation-reducing effect is greatest soon after rainfall. After prolonged drying, the amount of evaporation from residue-covered soil is about the same as from bare soil. Such empirical matters are useful to consider in the face of unqualified claims as to the universal desirability of mulching.

Saxton et al. (1988), while noting the water-conserving features of residue management techniques, also note that many farmers in dryland areas of LDCs have not adopted these techniques, choosing instead to use crop residues for animal feed, building material, and fuel. These authors suggest that this occurs because these farmers are not aware of the water-conserving features of residues. However, they also note (p.493) that "Results are lacking which show the economic value of crop residues for conservation relative to other uses." Since it is now well established that farmers in general are quite knowledgeable about the economics of their own
operations, and quick to adopt new practices when it is in their economic interests to do so, it is probable that, where farmers use crop residues for purposes other than water conservation, it is because the water-conservation alternative is relatively uneconomical. Anderson (1988) makes the same point about the economics of crop residue management, noting that use of residues for water conservation may have a high opportunity cost in situations where animal feed is an alternative use of residues. For this reason, "it is necessary to take a whole-farm view of residue utilization..." before concluding that residues offer a low-cost method for conserving soil moisture (Anderson 1988, p.154).

In India, results of pilot studies from watershed development projects indicate that plowing on the contour combined with vegetative bunding offers "scope for significantly improved water retention" (World Bank 1991b, p.51). The use of vetiver grass in the bunding is argued to be especially promising. The techniques can both reduce the susceptibility of crops to drought and lengthen the growing season by holding soil moisture longer than do current practices. Coupled with shorter and more water-stress tolerant varieties of cereals, pulses and other crops, these techniques have potential for "significant yield improvement" (World Bank 1991b, p.52). Moreover, the technology "is both easily replicable at the farm level and involves very modest investment costs, the core of the new technology only involving the very simple and low-cost practices of contour plowing and vegetative bunding, coupled with short-season varieties and some fertilizer" (p.52).

The use of vetiver grass, both to control soil erosion and conserve soil moisture, has attracted considerable attention in recent years. Writing on the subject of land degradation, Nelson (1988, p.13), has stated that, in dry areas, vetiver is "exciting, with potential for a significant impact..." on productivity. Writing of experiments he did with vetiver hedges to control erosion and runoff, Greenfield (1988, p.146) claimed that "Vetiver hedges take three seasons to establish, but once established they are permanent." Moreover "An established vetiver hedge will completely stop sheet erosion," and "silt trapped behind the grass barrier spreads back across the field...In Fiji, terraces 3 to 4 m high have formed behind the grass hedges." The cost of a vetiver system, according to Greenfield, is "at the very most one-tenth the cost of engineering systems" (p.146). And vetiver systems can be used on slopes of 45° (100 percent), which are too steep for presently-available engineered systems. Greenfield notes that vetiver grass systems have been introduced in Nigeria, Somalia, Sri Lanka and Indonesia (to name a few in addition to the already noted India and Fiji) and that, in fact, the systems can be used around much of the world.

The evidence described here indicates that there are a number of practices that, if the economics are "right," farmers can draw on to increase soil moisture, with favorable impacts on crop yields in areas where water is the principal limiting factor in crop growth. Much of the coarse grain production in LDCs is grown in such areas.

Although the technical feasibility of these water-conserving practices is well established, the fact that the practices have not been generally adopted by farmers is prima facie evidence that they are not generally economical. Research to overcome the economic barriers may have high payoff in higher coarse grain yields, especially in
dry areas. The issues are inherently complex and, as Anderson and Thampapillai (1990) argue, intrinsically uncertain in many respects, involving as they do a plethora of influences that bear on on-farm profitability. What seems clear is that farmers, as in their farm management generally, are sophisticated in their information gathering, their resource assessment and their decision making overall. It should come as no surprise then that, in recent field investigations by John Kerr (1992) and associates of Indian farmers' soil-management strategies, the farmers come across as highly sceptical assessors of technology, and entrepreneurial yet "responsible" (in an intergenerational or custodial sense) managers.

FSR and Increasing Productivity on Vertisols in India

These soils are deep (more than 45 cm) Vertisols that cover some 6 million ha in the wetter areas of semi-arid India. With traditional techniques, these soils are too sticky to be worked in the wet season and too hard when dry. Consequently, under the traditional system, they generally are used only for a single crop grown on the soil moisture left after the rains.

ICRISAT developed an almost completely new technology for cultivating these soils. The components of the technology were
(a) cultivation after harvest of the post-rainy-season crop; (b) land levelling and shifting, construction of field and community drains and the use of graded broadbeds and furrows; (c) dryseeding before the monsoons; (d) the use of modern crop varieties with moderate amounts of fertilizer; (e) improved placement of seeds and fertilizer, and (f) timely plant protection. Most of these steps can be most readily accomplished with a bullock-drawn wheeled tool carrier.

A study by ICRISAT staff in 1983/84, comparing the new technology with the traditional one at four sites in three Indian states, showed that the new technology cost about $70/ha more, but it increased average profits by $140/ha. A similar study on farmers' fields showed higher per hectare costs but still positive profits ($50/ha) for the new technology. Surveys of these farmers showed that some would continue to use the new technology. Observers in India, according to Anderson, Herdt and Scobie (1988, p.33), estimate that the technology was being used on about 4,000 ha of semi-arid rainfed land, mainly on land controlled by state governments. It was expected that implementation of a watershed project would encourage wider adoption of the technology in the states of Karnataka, Madhya Pradesh and Maharashtra. Progress doubtless has been fostered with further refinement and cheapening of the technologies through local adaptive research.

Continuous Cropping on Acid Infertile Soils

The discussion in Chapter 3 indicated that traditional farming practices on the acid infertile soils characteristic of much of the tropics result in low yields and severe

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¹The account of this research is based on Anderson, Herdt and Scobie (1988, pp.32-3).
loss of soil productivity after two or three years of cultivation. Research over the past 10 or 15 years suggests that, with adoption of new management practices, these soils can be much more productive on a sustainable basis. Buringh and Dudal (1987, p. 33) assert that

"Various experiments have clearly shown that many deep tropical soils can be permanently cultivated if an appropriate management is applied: the main problem of these soils is not irreversible hardening or laterite formation, as is often believed, but the aluminum toxicity that can be corrected by liming. A poor nutrient status is corrected by appropriate fertilization."

Note that this statement deals with corrective technologies now widely available, not with development of entirely new technologies.

Olson writes that several examples exist worldwide of situations where low productivity brush or sandhills have been converted to productive land by the introduction of fertilizers "and other appropriate agronomic practices" (Olson 1987, p. 216). One of the best of these examples is on the Cerrada soils of Brazil and Colombia. The climate in this region is favorable to crop production. The combination of liming and phosphorus fertilization overcomes the aluminum toxicity of these soils and, with appropriate use of nitrogen fertilizer, permits "thrifty" production of grains and soybeans on what otherwise is low-productivity rangeland. Olson further asserts that, with these practices and control of erosion "within reasonable limits," the large area of Cerrada soils would be a major source of food and fiber "for centuries to come." Indeed, with proper fertilization and pest control measures, "Vast areas of the humid tropics where either bush fallow has been practised traditionally, or no farming at all, have the potential for transformation to continuous agricultural production..." (Olson 1987, p. 216).

Olson does not say so but some of the research to which he referred likely was that done by a team headed by Pedro Sanchez, a soil scientist who worked at North Carolina State University. Reporting on that research, Sanchez et al. (1982) stated that they had developed technologies that permit continuous production of annual crops on some of the acid infertile soils in the Amazon Basin. Studies in the region show that three grain crops can be produced annually with appropriate use of fertilizer. In the 8 1/2 years preceding the report, 21 crops were harvested in the same field with annual average production of 7.8 t/ha of grain. (In the American Midwest annual yields of maize currently average about 7.5 t/ha.) Sanchez et al. reported further that, under this regime of continuous cropping, soil properties improved. A number of farmers in the region were induced to try the production system on parts of their land. The first eight who participated obtained yields comparable to those obtained at the research station. Sanchez et al. (1982, p.825) assert that "farmers are attracted by the prospect of increasing their yields six-to-tenfold (their traditional average is 1 t/ha/y) while avoiding the need to clear new land every year." Other more long-term field results elaborating the findings of this group are emerging (e.g., Sanchez, Palm and Smyth 1990). The results provide new and substantive data underpinning an optimistic assessment as to effective and sustainable cropping of tropical soils.
Conclusion

The economic and scientific resources necessary to develop the new technologies and management practices discussed in this chapter will be beyond the reach of many LDCs, indicating the need for closer cooperation among agricultural research institutions around the world, and especially between those in MDCs and LDCs. Duvick (1991) sees a special role for the international agricultural research institutions in promoting the needed increase in cooperation. But many other innovative changes in both national and international arrangements for agricultural research will surely also be required (Ruttan 1991, pp.403-6), including accelerated attention to resource management issues. The contemporary changes in and expansion of the CGIAR are encouraging in this regard, and instructive of the responsiveness and adaptability of the knowledge-based agriculture of the present and the future about which, presuming continued strong support both nationally and internationally, we have expressed such cautious optimism in this chapter.

Were such support not forthcoming on a continuing and reliable basis that permits successful undertaking of research work that is intrinsically long-term in nature, our somewhat sanguine summary of technological optimism would turn to one of alarm. Those with influence over the needed financial support, especially for international agricultural research, must be alert to the long-run consequences of any faltering along an already challenging path.
CHAPTER 10
SYNTHESIS AND CONCLUSION

Introduction

The preceding nine chapters reveal some features of special importance to thinking about the main threats to the long-term sustainability of the global agricultural system and about the policies for countering the threats. These features have both a demand side and a supply side.

The Demand Side

The most significant feature of the demand scenario is the much faster growth in LDC demand for coarse grains (216 percent) than for wheat (190 percent) and rice (105 percent) from the late 1980s to 2030 (calculated from Table 2.4). Among the three grains, rice in 1988/89 accounted for 35 percent of global consumption, coarse grains for 34 percent and wheat for 31 percent. The emergence (in the demand scenario) of coarse grains as by far the most important kind of grain is noteworthy because, as indicated in Chapter 9, little of these crops, relative to rice and wheat, is grown under irrigation or favorable rainfed conditions. This was given as one of the reasons why coarse-grain yields did not grow as rapidly over the past several decades as did yields of rice and wheat. Chapter 4 on the water resource indicated that there is still potential for expansion of irrigation in the LDCs. But unless the obstacles to irrigated production of coarse grains are overcome, this potential would contribute little to expanding production of the crops for which, in the demand scenario, demand increases most rapidly. Relative to the period since the 1960s, much more of the future increase in production would be on less-well-watered rainfed land, not only because additional irrigation water will be scarcer but because much more of the increase in grain demand will be for crops that will continue to be less dependent on irrigation. Although much concern currently is expressed about the problems of increasing the yield potential for rice, the demand scenario, combined with yield experience in the 1980s, suggests that high priority ought to be given to stimulating yield increases in coarse grains under both rainfed and irrigated conditions.

The Supply Side

Priorities Among Natural Resources

Among the four categories of natural resources considered here, supplies of plant genetic resources appear least likely to constrain production responses to the demand scenario. The future supply of climate resources is much more problematic, especially among different regions around the world, but on a global scale there is little
reason to believe that the supply will be much different over the period to 2030 than it is now.

Supplies of land and water likely will prove much more constraining, with water presenting the most difficult problems. Because water is a "fugitive" resource, property rights are more difficult to establish in water than in land. The difficulty of establishing property rights explains why markets for irrigation water are much less developed than markets for agricultural land. The property rights problem also explains why most irrigation water in the world today is provided by national governments; and the absence of market discipline explains why so much of that water is poorly managed.

Although much land in LDCs is managed under common property resource (CPR) systems, communal property rights in those systems generally are well-specified -- not necessarily in written form -- and management of them, therefore, is reasonably efficient in the sense that, by and large, farmers take user costs as well as current costs into account. Although many CPR systems are under pressure from population growth, technical change and increasing commercialization of agricultural and forestry output, there is much evidence of an evolution of these systems toward substitution of private for communal property rights. So long as the integrity of the rights is maintained, the relative efficiency of land management should also be maintained.

Thus the fugitive nature of water makes it an inherently more difficult resource to manage in a socially efficient way than land. We did not discuss how this difficulty might be overcome -- how enforceable property rights in water might be established -- and how alternative modes for strengthening incentives for more socially efficient use of irrigation water might be put in place. In thinking about priorities for action to expand supplies of agricultural land and water in LDCs, we conclude that action to deal with the water management problems should be in first place.

Priorities Among Economic and Environmental Costs

Within the existing knowledge regime, it will prove much more difficult to contain environmental costs than economic costs in meeting the demand scenario. This is for the same reason that it will prove more difficult to extend the supply of irrigation water than the supply of land: the structure of property rights. The present structure provides no incentive to farmers to take account of the environmental costs of their operations. They also lack incentive to control off-farm economic costs, but these surely are a small percentage of total on-farm and off-farm economic costs. (Recall from the detailing of our assumptions and definitions in Chapter 7 that off-farm economic costs are reflected in agricultural commodity prices. All environmental costs are off-farm and are unpriced.)

We are not prepared to suggest more than the most tentative priorities among the three kinds of environmental costs we considered--those of pesticide and sediment damage and losses of biological diversity from tropical deforestation -- because so little is known about them. We are most concerned, however, about losses of biological diversity, both because of the demonstrated high value of the resource in the past and because losses of it are permanent. We are less concerned -- again in a tentative
judgment — about costs of pesticide damage than about costs of sediment damage. The judgment is based largely on the trends in pesticide use, discussed in Chapter 7, toward less persistent materials, less reliance on insecticides and, perhaps paradoxically, toward more acutely toxic materials. The argument for viewing the latter trend as favorable is that the damages of highly toxic materials are immediately apparent and, therefore, more readily controlled than those of less acutely toxic but still threatening materials (such as DDT) that linger in and pervade the environment.

Current ignorance about the three kinds of environmental costs, and about others as well, strongly indicates that more resources should be devoted to research directed at reducing the ignorance. This kind of research should be systematically included in the programs of CGIAR institutions and in those of national agricultural research systems as well.

Alternative Environmental Policies

More research is needed also into policies and institutional forms that would induce farmers to take environmental costs into account, either by threatening them with penalties if they do not or rewarding them if they do. Regulatory approaches generally rely on the first kind of inducement, incentive approaches on the second.

To date, regulatory approaches have dominated environmental policies in all countries, but less so in agriculture than in other sectors. Because agriculture is more spatially diffused than most manufacturing industry, it is usually regarded as a "non-point" source of environmental damage. Enforcing regulations to control non-point sources generally is difficult and expensive because of problems of identifying the sources of pollutants. Many if not most farmers in a watershed, for example, contribute to downstream sediment damage, as does natural erosion. In these circumstances, designing regulations that are both effective and seen as equitable by the farmers affected is difficult. In the U.S.A., where soil conservation programs probably have more history and involve a larger commitment of public resources than in any other country, it was not until the 1985 Farm Bill that something like a regulatory approach was taken toward soil conservation. The Bill requires that farmers who wish to be eligible to participate in government price and income support programs must have acceptable soil conservation measure on their land by the mid-1990s. However, even this approximation to a regulatory program includes provision of public financial assistance to farmers to install the required soil conservation measures.

The only strictly regulatory approach to dealing with environmental costs of agriculture is with respect to pesticides. We have not canvassed the evidence on this, but it is our understanding that virtually all countries have some kind of regulatory program to exercise a measure of control over pesticide use. These programs doubtless are of varying degrees of effectiveness, and some of them likely are quite ineffective. Even those that are effective in the sense of accomplishing statutory or administrative objectives may, in fact, be wide of the mark in reducing environmental damages because of skimpy or erroneous scientific data about the fate and effects of pesticides in the environment. Nevertheless, we believe that, until economical
alternatives to pesticides are available, there is a compelling case for regulatory approaches to management of these materials.

A fundamental weakness in all regulatory approaches for control of environmental damage is that they require producers to act against their own perceived economic interests. Regulatory approaches, therefore, inevitably involve a bureaucratic apparatus to draw up regulations and a policing apparatus to assure their enforcement. The social costs of maintaining these regulatory institutions, including the costs of the conflicts between enforcers and producers, can be high. The higher they are the more attractive becomes the alternative approach of providing producers incentives to voluntarily adopt environmentally more friendly technologies. Subsidizing such technologies is one way to provide the needed incentives. But development economists are becoming increasingly skeptical of such subsidies. Those who receive them come to regard them as entitlements, and subsidies weaken incentives to search for technologies that would be economical without the subsidy, while also providing the desired level of environmental protection. Consequently, the agenda of agricultural research institutions should include development of technologies that at once are economical for farmers and environmentally more friendly than the alternatives now in use. Two examples of such technologies immediately come to mind: conservation tillage and integrated pest management (IPM). Conservation tillage includes a range of tillage practices, the significant common feature of which is that they leave sufficient stubble from the previous crop on the land to reduce erosion substantially. Such systems now are used on approximately one-third of the cropland in the U.S.A., and for the most part they are adopted and financed by farmers because it is in their economic interest to do so (Crosson, Hanthorn and Duffy 1986). Numerous studies have shown that conservation tillage systems can reduce erosion 50 to 90 percent on most sloping erodible land. The systems do not do as well as clear tillage plow systems on poorly drained soils or on those where perennial weeds are dominant. Most conservation tillage systems reduce or entirely dispense with cultivation to control weeds, relying on herbicides instead. Wider adoption of these systems may, therefore, involve a tradeoff between increased environmental costs of herbicides and reduced sediment damage. Studies undertaken in the U.S.A. indicate, however, that, as farmers gain experience with conservation tillage, their use of herbicides may increase little, if at all (Crosson, Hanthorn and Duffy 1986).

IPM seeks to control pests through a combination of biological agents, cultural practices and use of just enough pesticides to hold pest damage below the "economic threshold," i.e., that amount of damage for which, at the margin, the economic cost of damage equals the economic costs of the pesticides. In the U.S.A., IPM has been widely adopted in cotton production in Texas and on fruits and vegetables in California (Zilberman et al. 1991). It is a main reason for the decline in total pesticide use in the U.S.A. recorded in Table 7.3. Where IPM has been adopted in the U.S.A., it has been because it was more economically attractive to farmers than conventional control practices more dependent on pesticides.

This brief discussion of conservation tillage and IPM is intended to illustrate the point that development of more environmentally friendly technologies that are economically attractive to farmers offers an alternative to regulatory and subsidy approaches for dealing with the environmental costs of agriculture. Over the long run, resources devoted to developing such technologies may have higher payoff in reduced
environmental costs than resources devoted to formulation and enforcement of regulations and to payment of subsidies. At a minimum, the "new technology" approach should be included prominently among the policy alternatives for reducing environmental costs.

The Knowledge Resource

The main theme of this report is that, if the demand scenario is met at acceptable economic and environmental costs, it will be because the supply of knowledge farmers are able and willing to use increases enough to compensate for the insufficient supplies of land and water resources. In this argument, knowledge is the key resource and increasing the supply of it on economical terms to farmers is the key policy issue in achieving global sustainable agriculture. The argument rests on the notion that the supply elasticity of knowledge is greater than it is for land, water, genetic and climate resources. Experience over the past 50 years provides empirical support for the notion. It would be a mistake, however, to assume from this experience that the supply of knowledge will be as readily increased in the future as it was in the past. The past growth of knowledge did not "just happen." It was the result of a deliberate commitment of resources by public and private institutions and by farmers. It cannot be assumed that the future commitment of resources will be on the requisite scale or that the payoff to the resources will be as high as in the past. Whether the incentives of private institutions will be sufficiently strong and the political will and perception of need in public institutions sufficiently well-developed is problematical. And if the knowledge needed should involve major scientific breakthroughs, e.g., if expanding crop yields at the required rate should require substantial increases in photosynthetic efficiency, then even a large increase in commitment of research resources may not be enough to do the job.

Finally, it is not obvious how investments to expand the supply of knowledge should be distributed among human capital, institutional innovation and new technology. In Chapter 9 we concentrated on issues in developing new technology, but noted that knowledge embodied in people and institutions is also critically important in its own right as well as being highly interrelated. There is no reason to believe that the marginal returns to these three kinds of investment are the same. Indeed, a major question in devising a strategy to expand the supply of knowledge is how to allocate the necessary investments among people, institutions and new technology. We seek no answers to the question here. Our point instead is to emphasize that the issue of the scale of the needed investment in knowledge should be addressed simultaneously with the issue of the optimal distribution of the investment among the three forms in which the knowledge will be embedded. Clearly the problem of expanding the supply of knowledge on a scale and in a way required for a satisfactory response to the demand scenario will present political, economic and intellectual challenges of the first order.
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