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Demand and Supply of Foodstuffs up to 2050 with Special Reference to Irrigation

by

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Acronyms

CGIAR	Consultative Group on International Agricultural Research
CIMMYT	Centro Internacional de Mejoramiento de Maize y Trigo
EC	European Community
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographic information systems
ICID	International Commission on Irrigation and Drainage
IFPRI	International Food Policy Research Institute
IIMI	International Irrigation Management Institute
IMF	International Monetory Fund
IRRI	International Rice Research Institute
O&M	Operation and Maintenance
OECD	Organization for Economic Co-operation and Development
TAC	Technical Advisory Committee of the CGIAR
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNDP	United Nations Development Programme
WHO	World Health Organization
WRI	Water Resources Institute

Executive Summary

THE FIRST PART of this report (Chapters 1-IV) deals with the supply and demand for food up to the years 2025 and 2050 and role of irrigation in increasing the supply of food; the second part (Chapter V) lists some "researchable" topics that might be of interest to the International Irrigation Management Institute (IIMI) and other organizations. Projections of future supply and demand are difficult enough when one has good data; the limited quality and quantity of data on irrigated agriculture make projections in this sector exercises in "futurology." Nevertheless, it is important to make the best estimates possible, to enable planning for meeting future needs.

Between 1960 and 1990, the estimated food availability per person in the world has increased by 17.5 percent, and in the developing countries by 27.6 percent per person. The largest increases have been in China (55.5%) and the lowest in Africa (10.5%). Unlike the 1960s, there is now enough food in the developing countries as a whole to provide for the basic needs of all. This is a significant achievement, even though there are still shortfalls in supply in parts of Africa and a large amount of poverty-induced hunger in Asia and Sub-Saharan Africa.

In contrast with earlier experience, when *most* of the increased agricultural output came from expanding area, the increase in supply has been accompanied by a sharp rise in yields of the major staple crops. Between 1960 and 1990, cereal production in the developing countries grew by 118 percent. As much as 92 percent of that increase came from higher yields per hectare and only 8 percent came from expanding area under cultivation. The largest growth in yield was in the land-scarce economies of Asia; the smallest, in land-abundant Latin America and Sub-Saharan Africa.

The increase in yields was brought about in large measure by the introduction of high-yielding varieties of crops interacting with fertilizers, and assured supplies of water. Between 1960 and 1990, 80 percent of the area under rice and wheat, and 50 percent of the area under corn, was planted with modern varieties. At the same time, fertilizer consumption more than doubled and the area under irrigation expanded by 70 percent.

In the future, it is expected that population growth rates will decline sharply (other than in Africa and the Middle East), while incomes will rise substantially in all regions except Sub-Saharan Africa. When these factors are taken into account, along with assumptions about changes in tastes as incomes rise, the rate of increase in demand for food is expected to fall from around 3.1 percent a year to slightly more than 2.0 percent by the year 2025 and to about 1.5 percent a year by 2050. In Sub-Saharan Africa and the Middle East, demand will continue to grow by about 3.0 percent a year well into the next century, before slowing down.

Even though demand will increase at a slower rate than at present, most of the increases in basic foods will have to continue to come from substantial increases in yields, e.g., rice yields will have to double by 2025; average rice yields in Asia will therefore have to match current yields in Japan. However, it will be increasingly difficult to replicate past successes in raising yields, unless, among other things, greater attention is paid to improving the management of irrigation systems, especially in Asia.

Irrigation has been an important "engine of growth" in Asia (with 80 percent of the total area under irrigation in developing countries) and in the water-scarce areas of the Middle East and North Africa (with 10 percent of the total area under irrigation). The area under irrigation has expanded very rapidly in the post-war era and by 1989 close to 60 percent of the most widely produced and consumed basic staples, including more than half the rice and wheat grown in developing countries, came from irrigated land. Despite this important contribution, evaluations of irrigation projects have highlighted, and continue to highlight, the poor performance of many irrigation projects, and emphasize that many projects are operating well below their capacity.

In recent years, there has been a decrease in the rate of expansion of irrigation as real costs of developing irrigation projects have risen, and prices of cereal crops have fallen. Rising costs per hectare indicate a shortage of well-sited, low cost opportunities for further expansion. Significantly, it now also appears that earlier high rates of expansion of irrigation that helped fuel past high-growth rates in agricultural output may be unsustainable. While there is some scope for expansion, a continuation of past rates of expansion could exhaust irrigation potential in Asia well before 2025. Consequently, taking into account the poor performance of existing systems and the limits to further expansion, it is evident that there will have to be much greater reliance on raising yields from existing capacity if future demands for food are to be satisfied. This will call for greater emphasis on the improved management of irrigation systems to raise yields rather than looking to a rapid expansion of irrigation for increased output as in the past.

IIMI is concerned with improving the management of irrigation in developing countries. The Institute has the opportunity and capacity to undertake research on sector-wide issues as well as "cooperative" action-oriented research linked to its field operations.

IIMI is already undertaking research on important sector-wide topics such as the development of suitable performance indicators to assess the effectiveness of irrigation systems. These indicators are intended to include economic, environmental, engineering, and agricultural criteria and should become useful management tools, provided the research also shows managers how to use relevant performance indicators to enhance their operations. Another sector-wide research topic of global relevance could be to improve the present state of knowledge about the potential for increasing agricultural output from irrigated agriculture. This would include testing the hypothesis that irrigation potential in Asia is indeed reaching its limits, and how this may bear on strategies for agricultural development. The research could also examine what kind of yield increases might be expected from well-managed irrigated lands. This research could probably best be done in cooperation with other institutions in the CGIAR system.

Another sectoral topic of importance is an examination of the growing intersectoral competition for water. This would involve some analysis of how "managed demand" of water can best satisfy urban and rural needs, without reducing the capacity to raise agricultural yields. A further topic could be on the relative merits of large and small irrigation projects. This research is desirable in the light of the strong opposition by environmentalists to the construction of large reservoirs. This opposition may be constraining much needed expansion of the area under irrigation. The final sectoral topic that is extremely important is IIMI's research on institutional capacities and sectoral management. The adoption of improved management practices ultimately depends on institutional incentives and capacities; and profound changes are presently underway in the public and private sectors around the globe that will have important impacts on the sustainability and productivity of irrigated agriculture.

IIMI's action research already underway has provided valuable "reality checks" on the performance of on-going projects in selected countries. These reality checks have helped administrators and managers learn about problems in managing field operations and what might be done to improve the effectiveness of irrigated works under their jurisdiction.

Additional case studies that could lead to the improvement of irrigation water management are listed in the text. These include analysis of the extent to which the reallocation of water in surface irrigation projects can satisfy the twin objectives of improving equity and raising production, with a special emphasis on increasing yields. A further study would be an examination of the options regarding the nature and timing of the introduction of drainage to limit irrigation-induced salination, to provide guidance for managers concerned with these problems. Another topic for research could be a review and analysis of the validity of assumptions used in project preparation — the weakest link in the project cycle for irrigation projects — with a view to eventually strengthening project preparation, and hopefully reducing future needs for costly maintenance and rehabilitation.Similarly, an analysis of the availability of recurrent finances for implementing projects can test the widely held hypothesis that a shortage of these finances (not capital shortages) is a major constraint to improving the management and maintenance of many irrigation projects.

Other topics for action research could include an examination of the environmental impact of the intensification of production following the introduction of irrigation. The question to be examined would be how improved management of water flows could limit contamination arising from the greater use of agrochemicals. A broader, but important set of management issues that needs research arises from the very rapid spread of mechanical pumps and the continuous recycling of water. There is a need to know much more about the impact of these pumps on groundwater depletion and on the quality of water and how these factors affect yields. In this context, more needs to be known about how the proliferation of tubewells and pumps can be managed to limit resource degradation without unduly constraining private initiative.

IIMI has already undertaken important work in the decentralization of management and the partial turnover of surface irrigation systems to local user groups. Further work is to be encouraged as there is a great demand for information about this process, as more governments seek to shift the responsibility for operation and maintenance of irrigation works to water users. Yet another topic that warrants attention is how to adapt "traditional" irrigation systems near urban areas so as to diversify production to meet increasing demand for high-value crops such as fruits and vegetables. It is also suggested that, in recognition of the overall importance of the topic, IIMI should be encouraged to learn more about how gender issues bear on improving the management of irrigation projects.

Finally, the report has recommended that IIMI play a larger role in a cooperative effort to improve the very poor quality of data on almost all aspects of irrigation. Such a role would be consistent with a vision of IIMI as a center of excellence, and the major source of information about all aspects of irrigation and its development in the poorer communities of the world.

Introduction

THIS PAPER WAS commissioned by IIMI. It consists of two main parts, organized into five chapters. The first part (Chapters I-IV) responds to the call for an analysis of the demand and supply for food in the developing countries up to the year 2050; it also includes a discussion of the scope and importance of irrigation, the problems in implementing irrigation projects, and the prospects for further expansion of irrigated agriculture. The second part (Chapter V), which grows out of a combination of the author's experience and the analysis in the first part of the study, proposes recommendations on important "researchable" problems on irrigation and its contribution to producing food requirements for the future.

Projections of future demand and supply of food over the next half century are exercises in "futurology." Projections of demand are based on population growth, income growth and income elasticities. There is a great deal of information on projected growth in population; the World Bank very generously provided their best estimates of income growth over the next 50 years with the warning that their projections are speculative, at best. One of the important but debatable issues influencing income elasticities of demand is the extent to which people the world over will continue to buy more meat and dairy products as they grow richer. The assumption is that they *will* but if vegetarianism sweeps the world it will have a dramatic effect on the derived demand for cereals. It would also free resources, currently used to feed animals, to provide food for direct consumption by human beings.

The projections about supplies also involve conjecture about changes that might (or might not) occur. Most of the recent rapid increases in food production have come from increased yields per hectare. In the future there will be greater pressure to increase yields even further if demand is to be met from domestic resources. This raises questions about whether new technologies will be available, whether farmers will increase the use of agrochemicals and whether irrigation will continue to expand as in the past. Based on discussions with agricultural scientists, most notably with Dr. Borlaug, the father of the Green Revolution, it appears unlikely that there will be any dramatic technological breakthrough that can parallel the big boost given to yields in the 1960s; similarly the initial high gains from the earlier use of agrochemicals appears to be slowing down as diminishing returns set in; also the rate of expansion of irrigation appears to be slowing down. In light of this, while there is ample scope for increasing yields, the scenario for the next 35 years does not appear to be as comforting as it was 30 years ago when the new high-yielding technologies were beginning to spread across Asia. *Based on present technologies* it will be difficult indeed to increase yields in Africa and Asia to meet projected demand by 2050, so that without technological advances, especially in rice and wheat production, these regions will almost certainly become large grain importers. However, it is possible that there may be major breakthroughs in biotechnology as molecular biologists and geneticists unlock the secrets of how to increase genetic potential of the major cereals to a much greater extent than hitherto. This will be the next great breakthrough; hopefully it will come in the not too distant future.

The available data indicate that water is not yet a constraining factor on expanding irrigation except in the Middle East and North Africa. However, the prospects for sustaining past rates of expansion in irrigation in Asia are problematic. If the data on "potentially irrigable areas" as presented by the World Bank and UNDP are reliable then there will soon be limits on the scope for matching past rates of expansion to irrigation. The looming shortage of irrigable land reinforces the importance of using all land under irrigation as effectively as possible; more reliance will have to be placed on managing demand to prevent the wasting of water. However, it is not beyond the bounds of possibility that "climate change" will add to the water supply or that major discoveries in desalination will lead to making more water available for irrigation. Even so, it appears safe to assume that water will become a limiting factor in expanding agricultural production in many areas, unless steps are taken to manage existing supplies more effectively.

Two of the major conclusions of this study are that yields of the major cereals will have to increase substantially and that water will have to be used much more efficiently than in the past. The intensification of agricultural production to attain these ends will lead to greater environmental stress; balancing the need to increase output with safeguarding the environment (by reducing the use of agrochemicals, investing in more drainage, and the like) will make the task of raising yields more difficult rather than less difficult in the years ahead.

Chapter V of the paper assesses the poor quality of data relating to irrigation. Thereafter, a number of research topics are proposed that might clarify the present status of irrigation, identify future problems and contribute to the improved management of irrigation systems.

There are many unanswered questions about the role of irrigation in the future. IIMI should be in a position to contribute to improving the poor database on irrigation as well as in developing strategies and tactics for improving the efficiency of water use at all levels. In so doing IIMI will make a valuable contribution both to improving natural resource use and to increasing the output off irrigated land.

In undertaking this study I was fortunate to have access to information made available by many of my former colleagues at the World Bank and in the CGIAR system as well as advice on environmental issues from current colleagues at the World Wildlife Fund in Washington. I am especially indebted to Dr. Sam Johnson and Dr. Doug Merrey of IIMI for their constructive criticism of an earlier draft of this paper. As Program Leader for IIMI's program on Sector-Level Management of Irrigation Agriculture, Doug Merrey undertook to supervise preparation of this manuscript for publication (including some technical editing). The views expressed in this paper, though, are those of the author, not of the World Wildlife Fund in Washington or IIMI.

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CHAPTER I

Food Demand

1.1 INTRODUCTION

This chapter looks at the demand for food in the developing countries over the period 1990-2050, broken into 4 stages: 1990-2000, 2000-2010, 2010-2025 and 2025-2050. The demand and need for food is influenced by many factors including population growth, nutritional requirements, changes in income and the proportion of increased income used for purchasing food. These components are considered in the text that follows, which concludes with an estimate of the projected growth of demand for food in the developing countries as a whole, as well as in the major regions of the world; there are also estimates of the projected demand for cereals. Needless to add any such estimates, which are speculative at best, become more speculative as time horizons are extended. They should be seen as indicators rather than firm forecasts.

1.2 POPULATION GROWTH

Over the past 50 years, the size and the rate of population increase has been the most important factor influencing the growth in need and demand for food in the poorer countries of the world. By some estimates between 50 percent and 75 percent of the increases in the demand can be explained by the growth in population and the increasing numbers of mouths to feed. Thus trends in population have a great bearing on the demand for food. In recent years, the world's population has grown rapidly. In the post-World War II era, the population of the globe more than doubled, rising from 2.5 billion in 1950 to close to 5.3 billion in 1990, thus increasing at an annual average growth rate of close to 2 percent. Most of this increase took place in the poorer countries of the world where the population grew at an historically unprecedented rate of 2.3 percent a year, rising from 1.6 billion in 1950 to 4 billion in 1990. In contrast to this, the population in the richer countries increased by the slower rate of 0.5 percent per year, rising from 900 million to 1.3 billion over the 40-year period. The differential rates of increase in population between the poor and the rich countries have been such that the proportion of the earth's population living in poor countries rose from 60 percent in 1950 to 78 percent in 1990 [Population Reference Bureau 1992].

While the world's population has grown substantially, most population experts believe that a significant demographic transition has taken place in many — but by no means all — of the developing countries. This transition involves a series of stages characterized by high birth rates and declining mortality rates, causing high population growth rates, then a stage in which birth rates start to fall so that with lower birth rates and lower mortality rates, population growth rates start to decline. While this transition is yet to have its full impact, it appears that sometime in the 1970s population growth rates in the world started slowing down, falling to around 1.7 percent a year in the early 1990s [Merrick 1992]. The decline in population growth rates has been most striking in the developing countries where overall population growth rates have fallen from the previous average high rate of 2.3 percent per year in the 1970s to 1.9 percent at present. At this rate the population of the developing countries would double in around 36 years compared with 30 years doubling time at the old rate.

The most dramatic illustration of the demographic transition has been in China which, with a population of more than 1 billion people, has a proportionately large impact on the global situation. In China, mortality rates have declined sharply, with most of the decline, the first component of the country's demographic transition, being realized by the end of the 1960s. With falling death rates at a time of high fertility rates population increased rapidly. Thereafter, China adopted a series of "strategic demographic initiatives" which led to a rapid deceleration in fertility with birth rates plummeting nearly 50 percent between 1970-1979 from 34 to below 18 births per thousand. This huge slow down in child bearing was achieved in one decade, far less than the 50-75 years that most European countries took to accomplish this phase of the demographic transition. China's population growth rate fell from 2 percent to 1.3 percent in a short period and, provided these trends are sustained, could fall well below 1 percent a year by 2025 (and below 0.5% a year by 2050) [Hyaan Tien et al 1992].

The Chinese experience contrasts starkly with that in Sub-Saharan Africa. Birth rates in Sub-Saharan Africa are twice as high as those in China. Mortality rates have fallen from high levels as sanitation and health facilities, including the use of antibiotics, have become more widespread and nutrition has improved. Even so mortality rates are still relatively high compared with those in China, and have ample room to fall further. Sub-Saharan Africa has yet to enter the transition to lower fertility rates and lower mortality rates. In the interim, the region's population is growing rapidly by close to 3 percent a year and is expected to continue to grow, albeit at a slower rate in the future, averaging 2.3 percent a year up to 2025. By 2025, if present trends continue, Sub-Saharan Africa will have a population of over 1 billion people — a 150 percent increase above the present population; and by the year 2050 the population could well be over 2 billion.[1]

The future rate of growth of the world's population will depend in large measure on the actual change that takes place in fertility rates. The reasons for changes in fertility rates are not fully understood. There is widespread acceptance that rapid urbanization, along with improved education and greater employment opportunities for women, have a strong influence on fertility rates. In

1 In 1992, UN Population experts took account of the potential demographic impact of the AIDS pandemic in 15 countries in Africa where AIDS has highest prevalence. The conclusion is that "over the next 25 years population growth in these 15 countries could be 20 million less because of AIDS. Despite the substantial death toll, UN demographers project that population growth rates will remain strongly positive in the next few decades. The rapid pace of fertility will affect future population growth far more than mortality or any other demographic parameter." [Cited in *Population Today*, a publication of the Population Reference Bureau, Washington D.C., October 1992.]

addition, declines in fertility rates have been facilitated by the expansion of more effective national and international policies and programs for family planning and improving women's reproductive health [R.S. McNamara 1991]. However, there is a great deal of difficulty in foreseeing the rate at which change will indeed take place. This is amply demonstrated by the most recent UN projections which were modified in the light of "reality checks" based on updated information. A 1984 assessment projected global population reaching 10.2 billion by 2100; however, a 1990 assessment showed a global total of 11.3 billion for the same date [WRI 1992]. The projected further addition of more than 1 billion people by 2100 was attributed to a recognition that fertility declines in South Asia had been slower than anticipated on the basis of what seemed to be reasonable expectations. Population growth in the region had actually slowed down less rapidly than had been expected. The long-term consequences of even modest changes in fertility rates can be formidable and highlight the substantial differences that can arise depending on the assumptions that underlie these projections.

It is evident that caution is necessary in dealing with long-term population projections; nonetheless there is little doubt that there has been a decline in fertility rates and in population growth rates. Organizations such as the World Bank, the UN and The Population Reference Bureau all project these declines will continue. The World Bank projections of population growth rates — which will be used here — show a steady and substantial slowdown in overall annual population growth rates. The world's population is projected to grow by 1.60 percent a year on an average between 1990 and 2000 and by 1.12 percent between 2010 and 2025. Thereafter the average rate of growth over the next 25 years is expected to be around 0.83 percent a year. The same general pattern applies to the developing countries as a whole, with the population growth rate falling from an average of 1.92 percent a year in 1990-2000 to an average of 1.31 percent by 2025 and to 0.83 percent between 2025-2050 [see Table 1.1]. The population growth rates in the major continents of the world also taper off over the period 1990-2050. Growth rates are expected to fall below 1 percent a year in Asia and the Americas by 2025 and to much lower levels over the period 2025-2050. In Africa, however, growth rates only fall below 2 percent after 2025 and average over 1 percent between 2025-2050 [see Table 1.2].

There will be wide differences in population growth rates among different regions. The highest rates will be in Sub-Saharan Africa and the Middle East and North Africa, both of which start with a population growth rate of 3 percent a year. In Sub-Saharan Africa the rate declines to an average of 2.3 percent a year during the period 2010-2025 before going below this in the outer years of the projections. In the Middle East and North Africa, the rate declines much more slowly. The rate of growth of population in Latin America declines rapidly as the demographic transition is already well under way; the growth rates in South and East Asia also decline steadily from 1.8 percent and 1.4 percent a year to 1.0 percent and 0.7 percent respectively by 2025 and then are projected to decline to 0.8 percent and 0.4 percent over the next 25 years to 2050 [Table 1.2].

These declines in the rate of increase of population growth will lead to a relatively modest fall in the *absolute* annual increase in populations between 1990 and 2025, with a much sharper decrease thereafter. Between 1990 and 2025, the world's population is expected to rise from 5.2 billion to 8.4 billion and then will increase to 10 billion by 2050. The annual increase in population will average around 90 million people per year until 2025 before falling off to an average of 65 million over the next 25 years. As is shown in Table 1.1, most of the increase in population will take place in the developing countries; between 2025 and 2050 *all* of the global increases in population is expected to be in the poorer countries of the world. The largest increase will be in Asia where, despite the sharp drop in population growth rates, population will increase by 56 million people per year on average between 1990 and 2000 before tapering off to an average of 47.4 million per year over 2010-2025 and finally slowing down to 33 million per year, on an average, over 2025-2050. By 2050, it is expected that *Asia's* population will be well in the excess of the *world's* population in 1992 (5.7 million compared with 5.4 billion). Within Asia, South Asia will double its population from 1148 million to 2296 million over a 60 year period, while East Asia's population will increase by 60 percent from 1577 million in 1990 to 2126 million in 2050.

The most rapid increases are expected to occur in Africa, especially Sub-Saharan Africa. Africa's population will grow rapidly, rising from an average annual increase of 21.9 million in 1990-2000 to as much as nearly 30 million a year between 2010-2025. By 2010, Africa's population will exceed a billion people and is projected to increase to more than 1.5 billion by 2025 and to a staggering 2.2 billion by 2050. As is shown in Table 1.2, the pattern of increase is the same for Sub-Saharan Africa, with the population expected to increase from 492 million in 1990 to 1.3 billion by 2025, an increase of 150 percent over 25 years, to more than 2 billion by 2050. Given the region's current difficulties in providing food security for its population, an increase of this size signals problems ahead. The Middle East and North Africa's population is relatively small, being 6 percent of the total in the developing countries. However, it is expected to grow very rapidly, and more than double to over 600 million people in 2025 before rising by a further 50 percent in the next 25 years (a substantial increase in an area already suffering from a shortage of water).

The projected increases in population will lead to mega-countries and mega-cities. By the year 2000, it is projected that China and India will have populations of 1.26 billion and 1.01 billion respectively; by 2025 both countries will each have a population of 1.6 billion; together they will have around one third of the world's population, so what happens in India and China will have a large bearing on the global picture. Indonesia, Pakistan, Brazil and Nigeria will each have populations in excess of 250 million. By 2025, most of the world's population will be urbanized, with urban populations twice the size of the rural population of the developing countries (even so, absolute numbers in the rural areas will increase in all regions other than Latin America adding to pressure on land resources and the need for developing labor intensive forms of agricultural production). By 2050, it is estimated that at least 60 percent of the population in developing countries will be urbanized [World Bank 1992]. This rapid urbanization will result in the growth of mega-cities including a number of cities with populations of more than 10 million each. The growth of these cities and others will impose many challenges for the future, including the development of distribution systems and markets to provide food to many millions who will depend entirely on these markets for their subsistence. In addition, this growth of cities will lead to competition for scarce water resources that would otherwise be used for irrigation [see Chapter IV].

For present purposes the most significant aspect of the demographic landscape is that population growth rates are declining and are projected to continue to decline at a fairly rapid pace over the next 60 years. This is a welcome contrast from as recently as 1970 when population growth rates in the developing countries were projected to increase by *2.6 percent* a year by 1990 [Yudelman 1973]. The seemingly unstoppable increase in the rate of growth of the population has abated and is expected to continue to decelerate in the years ahead. Nevertheless, the need for food will increase substantially with the world's population projected to grow from 5.3 billion in 1990 to 8.4 billion in 2025 to more than 10 billion in 2050 with the population in the developing countries rising from 4 billion to 7 billion and then to 8.7 billion over the same period. The increases in population are projected to vary but the rapid increases in Sub-Saharan Africa and the Middle East and the vast increases in Asia will certainly pose special challenges to meeting demands for food in these areas.

1.3 BASIC NEEDS — NUTRITION

One of the important objectives of policy in most countries is to ensure that all citizens have an adequate diet or at least a diet adequate to meet basic needs. There are wide differences of opinion about what constitutes an adequate diet or a "minimum level of intake" [National Research Council 1991]. As a general rule, such a diet is defined in terms of calories/energy requirements (while recognizing the need for proteins, vitamins and micro-nutrients). A number of studies and surveys undertaken by WHO and FAO have established that calorie requirements per individual, per day vary depending on factors such as age, sex, physique, extent of physical activity, health and the climate in which individuals live and work. One such study in India and Egypt indicated that between 1,450-1,610 calories per day, and 1,550-1,720 calories per day, respectively, was the minimum maintenance requirement for energy for adults [Perkins 1991]. This did not include allowances for movement or work energy. Other studies show higher requirements for children and lactating mothers; yet others show large variation depending on individual body sizes and economic activities.

Currently the most widely used specifications for a diet that meets basic nutritional needs are those made by the FAO-WHO Consultative Group on Nutrition, which recommends calorie allowances based largely on age and sex for different levels of activity but with some differentiation to allow for body weight. According to many authorities concerned with food aid, a rough approximation of this approach would call for an average per capita allowance of around 2,200 calories per person per day to meet basic needs [Berg 1992]. This allowance would reflect an average across all population groups with a "typical" distribution of age groups. If some allowances are made for wastage and conversion of grain into protein then around 1 metric ton of grain equivalent per year could well meet the basic needs of a typical family of five.

The adequacy of any supply of food, however, depends on the composition of individual diets. For example, according to the World Hunger Project at Brown University in the USA, if all of the world's vegetative food and the products of range-fed animals were distributed equally among all the world's people, in line with WHO and FAO calorie standards, then there would be enough food to feed 5.9 billion people or nearly 13 percent more than the world's population in 1990. But if diets were to be improved beyond an essentially vegetarian diet to one similar to that which many South Americans eat today, with about 15 percent of the food calories coming from animal products, then there would be food enough for about 3.9 billion people or 75 percent of the world's population. Going further, if diets were to be improved to what is described as a "full, but healthy" diet, that incorporates the desires most people have for "rich and more varied diets" with about 25 percent of calories from animal products, then there would only be sufficient food in the world to feed as few as 2.9 billion people or 56 percent of the world's population [World Hunger Project 1991].

The use of resources to produce feed for animals preempts some of the land, labor and capital that could be devoted to producing grains for direct human consumption. If meat consumption were to decline, this could result in the same resources previously used for feeding cattle adding a disproportionately large share to the supply of calories for human consumption. One ton of grain produced for direct consumption yields seven times more calories than if the grain is converted to beef and then consumed. Livestock products accounted for less than 10 percent of the total calories consumed in the developing countries in 1989 [TAC 1992]; nonetheless it is estimated that as much as 100 million tons of wheat and corn, out of the 420 million tons produced in the developing countries, was used for animal feed in 1985 [CIMMYT 1989]. Theoretically if this grain could be used for human consumption it could have provided a basic diet for close to 500 million people. Thus, a shift in consumption patterns away from meat could in principle add substantially to the amount of calories available for meeting basic needs. In reality, though, because per capita incomes have risen in most developing countries, the demand for meat and dairy products, and the derived demand for grain for feed, is rising much more rapidly than is the demand for grain for direct consumption.

FAO estimates confirm that the global food supply as presently constituted is more than adequate to meet the basic needs to provide around 2,700 calories per person per day. This represents a 17.5 percent increases in calories available per person over the past 28 years (1962-1990). The increase in per capita calorie availability in developing countries as a whole has been impressive, rising by 27.6 percent from a level of 1,939 calories per person per day in 1962 to 2,474 calories per person per day in 1990. Regionally, the slowest increase in calorie availability has been in Africa with 10.5 percent per capita increase over the 28 year period while the most rapid increase has been in China which registered 55.5 percent per capita increase over the same period [see Table 1.3].

The world's food supply is not evenly distributed. Therefore, despite recent progress in increasing supplies there are still a number of countries that do not have an adequate supply of food to meet their basic needs. In 1990, the average daily per capita availability of calories in the developed countries was in excess of 3,400 calories per day while there were around 2,400 calories in the developing countries as a whole [Table 1.3]. The situation among the developing countries has improved substantially since 1961-1963. At that time there were 74 countries out of 115 that had an average food availability below 2,200 calories per person per day and 40 countries with an average food availability below 2,000 calories per person per day. By 1988-1990, however, the food supply has increased to the point where there were only 25 countries with an average of less than 2,200 calories per person per day and as few as 9 with an average that was less 2,000 calories person per day [see Table 1.4].

The distribution of available calories among the developing countries is skewed in favor of the richer countries. Of the 34 countries having an insufficient calorie supply to meet their basic requirements (as defined by FAO), 25 are among the poorest countries in Sub-Saharan Africa (which as a region was estimated to have a food supply which could only meet around 90 percent of its basic needs). The other poorer calorie deficient countries include three populous countries in

Asia: India, Pakistan and Bangladesh which in 1989 had an available food supply that could provide 92 percent, 94 percent and 83 percent respectively of the nutritional requirements [UNDP 1992]. In addition, Bolivia and several smaller countries in Central America and the Caribbean also had a calorie deficit. In very broad terms, there was a general calorie deficit of around 10 percent in the deficit areas of Asia and Africa, though the deficit was worse in some areas than others.

Countries with inadequate food supplies are also those with the largest numbers of undernourished citizens. There are several estimates of how many people fall into this category. The World Bank estimates that about 1 billion people in the developing countries are too poor to acquire at least 90 percent of the diet needed to meet their basic needs. FAO and WHO have recently estimated that 780 million people or 20 percent of the population in the developing countries are undernourished [FAO-WHO 1992]. This estimate is based on the construction of national food balance sheets and is checked by the use of household surveys. The Hunger project at Brown University, drawing on both sources, estimated that in 1990, around 1 billion people in the world had diets that were "energy insufficient for work" and that some 477 million people — 9 percent of the world's population in 1990 — lived in households "too poor to obtain the energy required for healthy growth of children and minimal activity of adults" [The Hunger Report 1991].

It appears reasonable to assume that there are around 1 billion people — close to 20 percent of the *world's* population in 1990 — who are undernourished with around 800 million of the ill-nourished living in the developing countries; close to 500 million people out of the 800 million fall into the category of being seriously effected by malnutrition. The most recent FAO world food survey indicates that the largest number of calorie-deficient consumers are in Asia. Despite great progress, whereby the proportion of "ill-fed" in Asia has fallen from 40 percent in 1970 to 19 percent of the population in 1990, there are around 500 million people who are unable to meet their basic food needs. Africa is the continent with the highest proportion of its population, nearly one third or around 170 million people, who are food deprived. The remaining malnourished are in Latin America and the Middle East; their numbers are a relatively small part of the total. The main concerns lie in Asia and Africa [FAO 1992].

There are enough calories available in the world at large and in the developing countries as a whole to meet the basic needs of the global population and the population of the developing countries. However, for such a goal to be attained there would have to be a transfer of food from the surplus areas to the deficit areas and to the ill-nourished within the different areas. The size of such a transfer to meet basic needs depends on the extent of the calorie deficiencies among the affected population. No one knows how large this is. However, rough estimates are that around 500 million people suffer from an average shortfall of 20 percent of their calorie needs and a further 300 million have a 10 percent deficit. If this is the case, then a one-time shift of some 26 million tons of grain equivalent would overcome the estimated calorie shortage in the calorie-deficit developing countries for one year (this represents substantially less than 1 percent of the grain produced in the developed countries). Thereafter the calorie deficit could be limited by continued transfers of grain, accelerating production in the developing countries, or by a combination of both.

If there are no transfers of grain to calorie-deficit areas then there will have to be a substantial increase in the supply of calories to accommodate existing shortfalls and to take account of the needs of a growing population. The *increase* in population of 86 million people a year between

1900 and 2025 would require an average increase of around 17 million tons a year and the projected increase between 2025 and 2050 would require an average annual increase of around 13 million tons a year [see Table 1.5].

If an additional 26 million tons of grain-equivalent has to be produced *each* year to erase the existing deficit, then there will have to be a sharp increase in production, possibly as much as 4.9 percent a year, on average, in the period 1990-2000 declining to around 4.4 percent up to the year 2025 and falling below 4 percent thereafter (current increases are around 3% a year). The most rapid increases in supply would have to be achieved in Sub-Saharan Africa where output would have to increase by 6.5 percent a year to meet current basic needs and those of an increasing population, before slowing down to about 5 percent a year in the outer years of the projection (current increases are between 2 and 3%). In Asia, where the largest number of malnourished people live, incremental output would have to more than double to meet basic needs before declining in the years beyond 2025 (current increase is around 3% a year).

The estimated increases in calorie requirements to meet basic needs are premised on a number of assumptions about shortfalls and about the nature of society (it should be noted that these estimates are of needs, not of how much would be needed to have an effective program). Furthermore the estimates of calory shortfalls among the malnourished are based on highly speculative data. There are also assumptions that diets would not change over time and that increments of supplies would be distributed in such a fashion that all would receive a ration adequate to meet their basic needs. Such assumptions, if they could indeed be fulfilled, would only be possible in a command economy where extra-market methods are used to control the distribution of food. There are few if any such command economies in the world today.

Currently there is a reliance on market mechanisms to distribute food. Despite the fact that there are adequate supplies of food, many consumers are unable to satisfy their basic needs. In this context the message is clear: even if output was to grow by the 4.9 percent a year to meet basic needs, such an increase in supplies would not be a sufficient condition to ensure that all consumers would be able to satisfy their needs. An added condition is that people must have the means to acquire their food in the market place. Consequently in a market economy, the sine-qua-non for meeting basic needs is not only that supplies must be adequate but substantial increases in incomes among the poor calorie-deficient population are necessary to enable them to purchase what they need.

1.4 ECONOMIC GROWTH AND DEMAND

Many factors influence changes in demand for food over a period of time. By and large, though, the bulk of the changes that take place can be explained by the interaction of three variables: population growth, changes in income and the income elasticity for food (the proportion of increased income spent on food).

Demand for food in the developing countries will increase as economic growth leads to changes in consumer incomes. Between 1950 and 1990 the economies of the developing countries grew at a very high rate. The average per capita incomes rose by 2.7 percent per year "*the highest sustained* *rate in history*" [World Bank 1992]. However, the pace of growth varied substantially among different regions. Asian countries with close to two thirds of the population of the developing countries, grew at an average rate of 5.2 percent a year in the 1970s and 7.3 percent in the 1980s. Growth in the non-Asian developing countries as a whole decelerated from 5.6 percent in the 1970s to 2.8 percent in the 1980s. On a per capita basis, incomes in East Asia and South Asia grew by 6.3 percent and 3.1 percent in the 1980s; during the same period, per capita incomes declined in Sub-Sahara Africa, Latin America and the Middle East.

The world's economy is currently in a period of very slow growth that contrasts markedly with the buoyant years of the 1960s and 1970s. There is a great deal of uncertainty about the prospects for future growth. The International Monetary Fund, The Organization of Economic Cooperation and Development (OECD), and The World Bank have made short-term projections of growth up to the year 2000, and the Bank and OECD have also made longer-term projections [M. Brown and I. Goldin 1992]. There is a general consensus that growth in the industrial countries will be slower in the 1990s than in the 1980s; however it is projected that the economies of the developing countries will grow at a faster rate (by 5%) in the 1990s than they did in the 1980s (3.4%). This higher growth rate is premised on continued economic reform in the developing countries with changes in the domestic policies more than offsetting any changes attributable to deteriorating external conditions [World Bank 1992].

Growth in incomes in Asia is expected to slow down from the high levels in the 1980s but at 4.8 percent per capita will continue to be above the average for developing countries as a whole, expected to be around 2.9 percent per capita. Incomes in Sub-Saharan Africa are expected to rise by a very modest 0.3 percent per capita while in Latin America and the Caribbean they will increase by an average 2.2 percent per year [see Table 1.6].

Projections have been made up to 2025 by the World Bank and OECD; these have been extended up to 2050. These projections are based on "historical experience" leavened by the judgment of the economists in these organizations (in the case of the World Bank it is emphasized that the projections should be seen as indicators of what seems likely to occur rather than a precise forecast of the future). It is expected that average incomes in the developing countries could triple in real terms from the current average of $750 today to about $2,250 in 2025 and double again by 2050. By 2050, it is expected that the developing countries' share of world income will have risen from less than one quarter to one half of the global total.

The most rapid growth rates are expected in Asia, particularly in East Asia where per capita incomes are expected to grow by more than 4 percent a year between 2000 and 2025, with per capita income reaching around $3,000 by 2025 and over $6,000 by 2050. In South Asia, per capita incomes will grow by close to 3 percent per year over the period up to 2025 reaching around $1,000 per capita in 2025 and over $2,000 by 2050. The average per capita incomes in Latin America, Middle East and North Africa will grow between 2.5 and 3 percent over the period of 2000-2025 and by between 2 percent and 2.5 percent thereafter. The average per capita income in Latin America, and Middle East and North Africa could be more than $5,000 and $4,000 respectively by 2025 and $8,000 to $7,000 by 2050. The slowest per capita increase in incomes will be in Sub-Saharan Africa, where per capita growth is expected to be less than 1 percent per year between 2000 and 2025; per capita incomes would thus be less than $400 by 2025; thereafter with a higher growth rate they could reach around $800 by 2050 [World Bank 1992].

The projected increases in incomes in the developing countries will lead to an increase in per capita demand for food. As incomes rise demand will increase, but it will increase at differential rates depending on the levels of incomes of consumers. It is well established that low income consumers will spend a larger proportion of a given increase in income on additional purchases of food than will higher-income consumers, i.e., the income elasticity with respect to the demand for food is higher for the poorer consumers than it is for the rich. The affluent already spend a higher amount for food and have other preferences for spending their additional disposable income. Considerable uncertainty exists as to what average elasticities are. A central problem is that national averages reflect assumptions about income distribution. Income elasticities are high for cereals at the bottom and top ends of the income profile: at the bottom end because of the desire to increase consumption and at the top end because of a strong demand for livestock products which are cereal intensive. There are a number of estimates. The income elasticity for the developing countries as a whole, with an average per capita income of around *$750* dollars per year, is placed at 0.4 percent [Anderson 1992]. This compares with 0.1 percent for the developed countries as a whole with an average income in excess of *$20,000*. On average, consumers in the developing countries spend an estimated 40 cents out of every additional dollar in income on food, while consumers in the developed countries only spend 10 cents out of every additional dollar of disposal on food.

Among the developing countries there will be a range of income elasticities for the demand for food depending on the levels of the income and the growth of incomes in the years ahead. IFPRI has made estimates of income elasticity for the demand over food for the period 1990-2000. These estimates show a range in income elasticities from 0.6 to 0.2 for the different regions. The highest elasticities are in the poorest regions, Sub-Saharan Africa and South Asia, where 60 percent and 40 percent respectively of any increase of income is expected to be used to purchase food. The lowest income elasticities of demand for food are in the more affluent regions where incomes are projected to rise rapidly. Income elasticities are estimated to be 0.2 in East Asia, 0.3 in Latin America, and 0.3 in the Middle East and North Africa [Table 1.6].

Over the longer run (2000-2025 and 2025-2050), as incomes rise, in line with Engel's Law, a decreasing proportion of the increasing income will be spent on food. Thus the income elasticity of demand for food will decline over the years ahead as average per capita incomes rise substantially in East Asia and Latin America. By 2025 these regions should have income elasticities similar to those of the developed countries of today (0.1 and 0.2 respectively); changes are expected to be less significant in South Asia and Sub-Saharan Africa where there will continue to be a very large number of low-income consumers.

The combined effect of population growth, increases in income and changes in income elasticity of demand for food will account for the bulk of changes in demand for food. These factors are summarized in Table 1.6 for the time periods 1990-2000, 2000-2010, 2010-2025 and 2025-2050. The rate of increase in demand for food in the developing countries as a whole is expected to fall steadily from an average of 3.1 percent a year in 1990-2000 to 2.8 percent between 2000-2010 and then to 2.1 percent over the period of 2010-2025 before falling even further to 1.6 percent a year over the period 2025-2050. This rather sharp decline in the rate of increase in demand is attributable largely to the projected drop in population growth rates and to declining income elasticities of demand. Within the regions, the pattern of declining rates of growth of demand will vary; all regions other than the Middle East and North Africa will have steadily declining rates of increase in demand with the largest drop being in East Asia where, despite rapid growth in per capita income, the low elasticity of demand will slow down growth in demand for food; the same applies in Latin America. In Sub-Saharan Africa, a high rate of population growth combined with low income growth and a high income elasticity will lead to a continued high rate of demand for food up to 2025 before the rate declines in the outer years of these projections. The resulting changes in demand over time for the developing countries as a whole and different regions are given in Table 1.7.

1.5 CEREALS

Changes in income influence the composition of demand. The most important component in the food basket in the developing countries is cereals. Cereals include rice, wheat, corn, millet, sorghum, rye and barley. Global production of cereals in 1989-90 was 1,880 million tons of which there were 600 million tons of wheat, 400 million tons of rice, and 850 million tons of coarse grains, with corn being the most important of the coarse grains. Close to 52 percent of the global supply of cereals is grown in developing countries including about 94 percent of the world's supply of rice, 50 percent of the world's wheat supply and around 40 percent of the supply of coarse grains (including 39 percent of the world's corn supply). Overall, cereals accounted for about 83 percent of the major food production in developing countries in 1980, with the remainder consisting of roots and tubers (11%), cassava (3%), ground nuts (2%) and bananas and plantains (1%) [Paulino 1986].

Regionally, Asia is the largest producer and consumer of grain, accounting for about 75 percent of all the grain produced and consumed in the developing countries (China alone accounts for 36% of this total). Africa and Latin America each account for about 12 percent of the consumption of the developing countries. Cereals are less important in Africa than elsewhere because African diets contain a high proportion of roots and tubers. Unlike the other major regions, only 55 percent of the food supply in Sub-Saharan Africa consist of cereals, compared with 86 percent in Asia and 79 percent in Latin America.

The consumption of cereals in the developing countries has risen from 170 kg per person per year in 1960 to 236 kg per person per year in 1990. This contrasts with an increase from 483.6 kg per capita per year to 570 kg in the industrialized countries over the same time period. Cereal consumption in the developing countries grew by about 3 percent annually over this period with the largest increases being in the period 1970-1980, a time of substantial economic growth, before slowing down to 2.5 percent in the period 1980-1990. Among the cereals, the most rapid increases in consumption over the thirty-year period have been in wheat, which has grown by around an average of 4.5 percent a year. The slowest has been in rice, which has grown by 2.7 percent a year on average over the same period. During the thirty-year period per capita consumption of wheat rose from 38.6 kg per year to 70.6 kg per year while that of rice grew from 68.5 kg per year to 83 kg per year.

"Bennett's Law" states that the "staple ratio," which is the proportion of calories an individual derives from basic staples, declines with rising incomes. There are several estimates of future demand for individual cereals and for cereals as a group that support this observation. Generally, studies confirm that cereal consumption will increase, but at a decreasing rate similar to that of all foods as incomes rise (as discussed above). The World Bank projects demand for cereals will grow by 2.5 percent a year between 1988/89 and 2005 and by 2.3 percent a year between 2005 and 2030 [Crosson and Anderson 1992]. These estimates are somewhat on the low side in the light of growth rates since 1988/89, especially in Asia. Revised estimates based on the author's analysis are that demand for cereals could well rise by 3.3 percent between 1990 and 2000 before slowing down to around 2.3 percent between 2000 and 2035 and around 2.2 percent between 2025 and 2050 [see Table 1.8].

The demand for different cereals will be influenced by a number of factors that include everything from the relative prices of grains to social customs and preferences. Other important factors include the effects of urbanization and access to convenience foods, especially when there is less leisure time for urban families to prepare time-consuming traditional dishes. Urbanization has hastened the shift towards wheaten bread in many parts of the world. Food aid programs that led to changes in relative prices of commodities have also influenced patterns of consumption, especially where the subsidized imports have been widely distributed. This has happened in several countries where low-priced, imported wheat has displaced domestically produced coarse grains. Improvements in literacy, education campaigns and advertising have also influenced consumer preferences over time.

The most pronounced effects on shifts in demand for individual cereals come from changing tastes as incomes rise. This is most evident in the growth of "derived" demand for cereals used as animal foodstuffs, and in the shift away from rice as a basic staple in some Asian societies. The income elasticity of demand for meat is close to unity in many developing countries and is also high for milk and eggs. Most of the cereals — wheat, rice, sorghum, millet, barley and corn — are used as animal feeds depending on local availability, tradition and relative prices. Sorghum and millet are widely used for animal feeds in West Africa and wheat is used in some parts of India, while rice is used to feed chickens in much of Asia. However, the great bulk of all the cereals used for animal feed is provided by corn, with about 60 percent of total corn consumption in developing countries being used for this purpose.

Corn, like other coarse grains such as millet and sorghum is also consumed directly, especially in Africa, Central America and Mexico and parts of Asia. The demand for corn for this purpose has been growing slowly, averaging around 2 percent a year over the past thirty years. In contrast to this, the demand for corn as animal feed has risen by close to 5 percent a year over the thirty-year period. Over the past decade the fastest growth in demand has been in Asia (5.5%) though there has also been an appreciable increase in demand in Latin America (3.6%) and the Middle East (4.1%) [Brenner 1992].

The future demand for corn and coarse grains will depend largely on the rate of increase in the consumption of animal products. With rising incomes, it is expected that the demand for animal products will continue to grow rapidly and so will the demand for animal feed. The demand for corn as a food will also continue to grow but at a slower rate as population growth rate slows down.

The projections made by the OECD and CIMMYT are that demand for corn will increase by 3.5 percent a year on average over the period 1985-2000. However, the slow growth in the early part of this period makes it extremely unlikely that this projection will be fulfilled; a more realistic projection for the years 1990-2000 would appear to be around 2.5 percent a year. The growth in demand for the other coarse grains, consumed largely as food, especially millet and sorghum, is expected to be close to the rate of increase for population so the rate of increase in demand for all coarse grains will be around 3.0 percent a year (this is in line with the World Bank's estimate of demand up to 2005). Over the longer-run, up until 2025, the demand for coarse grains, especially corn for animal feed, is expected to continue rising. Both the World Bank and FAO project an increase in demand averaging 3.2 percent a year upto 2025. This is consistent with the notion that the demand for meat will rise very sharply as incomes rise over time.

The demand for wheat is expected to continue rising at a rapid rate over the foreseeable future. It is expected that urbanization and higher per capita incomes will induce consumers to increase per capita consumption at the expense of traditional foods. There is a general consensus among FAO, CIMMYT and the World Bank that the demand for wheat will increase by around 3 percent a year up until 2000. The most rapid increases are expected to be in Sub-Saharan Africa, 5.1 percent per anum, and 2.9 percent in other regions. The World Bank and FAO also expect wheat consumption to continue increasing but at a declining rate over the longer run, rising by an estimated 2.3 percent a year up until 2025 and continuing at less than that rate to 2050. The main reason for the slowing down in the rate of increase in demand is the decline in the rate of population growth; however, recent trends and the high income elasticities of wheat and the projected rapid rate of urbanization give reason to expect a higher rate of demand for wheat than the rate projected by the Bank. Wheat demand is expected to increase by 3.0 percent up to 2025 and by 2.5 percent between 2025 and 2050.

There is a general expectation that the demand for rice will follow the pattern that has taken place in recent years in Japan, Korea and Taiwan. As these rice consuming societies have become increasingly affluent, there has been a shift away from the heavy reliance on rice towards a more diversified "western" style diet (with a large increase in wheat and wheaten products, meats, dairy products, vegetables and fruits). In Japan, per capita consumption of rice declined slightly between 1960 and 1980 at a time when wheat and coarse grain consumption were rising by as much as 6 percent a year, on average, over the period. The OECD, FAO and the World Bank project that rice consumption will rise by a slightly lower rate than in the past (by between 2% and 2.4%) up to 2000.

Over the longer run, as Asian societies develop and grow, there will probably be a shift similar to that in Japan and Korea. The World Bank expects demand to slow down and grow by an average of 1.7 percent a year by 2020 (a projection that is well below that made by the International Rice Research Institute [IRRI]. If there is broad-based growth in Asia, increasing incomes among the billions of very poor consumers, then demand should rise more rapidly than projected by the Bank. It is assumed this will happen and so consumption will rise by 2 percent a year from 1990 to 2025 before declining to 1.5 percent a year between 2025 and 2050.

1.6 SUMMARY

The overall pattern of demand will be heavily influenced by population growth and to a lesser extent by increases in income. If population growth rates decline, as projected, then, by and large, the rate of growth of demand for food will decline; if per capita incomes increase as expected, the demand for animal feedstuffs and wheat will rise at a faster rate than for rice. Other points emerging from this analysis are as follows:

a. The basic needs of all people could be met if available food supplies were equally distributed among all the world's citizens. Failing this, there will have to be much higher growth rates in supply than at present to meet the basic needs of all the citizens of Sub-Saharan Africa and Asia.

b. Consumers in urban areas have benefitted from increases in real per capita incomes at a time when prices of basic staples fell. Between 1970 and 1990, per capita incomes, especially in Asia, were rising at an unprecedented rate while prices of rice and wheat fell by around 50 percent and 35 percent respectively. The fall in the price of staples probably helped poor consumers — who allocate a large proportion of their income to food — more that it helped rich consumers. Despite this, somewhere between 500 million and 800 million people living in the developing countries are too poor to satisfy their basic needs.

c. Demand for food in the developing countries is expected to grow by an average rate of 3.1 percent a year up to 2000 A.D., then by an annual rate of around 2.5 percent up to 2025, and by less than 2.0 percent up until 2050. The most rapid and sustained rate of increase in demand, more than 3 percent a year, will be in Sub-Saharan Africa and the Middle East. There will be a steady decline in the rate of growth in demand for food in Asia; demand in South Asia will grow by 3.1 percent a year before declining to 1.9 percent between 2025 and 2050; in East Asia, demand will decline from 2.6 percent a year to less than 1 percent between 2025 and 2050; in Latin America, demand will fall from close to 3 percent in 1990-2000 to less than 1 percent by 2050.

d. Demand for all *cereals* is expected to rise by around 3.3 percent a year up to 2000 A.D., before declining to 2.3 percent a year up to 2025 and to 2.2 percent a year up to 2050. Demand for wheat is expected to continue to rise by 3.5 percent up to 2000 A.D. and then decline in the years up to 2050. Demand for coarse grains, including corn (largely for animal feedstuffs), is expected to rise by 3.0 percent up to 2000; by 3.2 percent up to 2025 and by 3.0 percent thereafter up to 2050. The demand for rice is expected to grow more slowly than these cereals, increasing by 2.7 percent a year up to 2000 A.D. and then by 2.0 percent a year up to 2025 and by 1.5 percent a year to 2050.

Table 1.1. Total Population, Annual Increase and Growth Rates for the World, Less Developed Countries and More Developed Countries.

Total Population (millions)			
Year	World	Less-Developed Countries	More-Developed Countries
1990	5285	4074	1211
2000	6204	4939	1265
2010	7112	5808	1304
2025	8415	7078	1336
2050	10035	8716	1310
Annual Increase (millions)			
	World	Less-Developed Countries	More-Developed Countries
1990-2000	92	86	5.0
2000-2010	90	87	3.9
2010-2025	87	85	2.0
2025-2050	65	65	–
Growth Rate (percent)			
	World	Less-Developed Countries	More-Developed Countries
1990-2000	1.60	1.92	0.44
2000-2010	1.37	1.62	0.31
2010-2025	1.12	1.31	0.16
2025-2050	0.83	0.83	–

Source: World Bank

Table 1.2. Population Increases and Growth Rates by Continents and for Selected Regions 1990-2050.

	Population Increase (millions)							
	Africa	Sub Saharan Africa	America	Latin America & Caribbean	Asia	South Asia	East Asia	EMENA*
1990	651	492	721	441	523	3664	1377	1818
2000	870	721	826	523	3664	1377	1818	341
2010	1139	993	918	601	4190	1588	2038	441
2025	1587	1382	1040	709	4901	1896	2276	615
2050	2275	2064	1146	754	5728	2296	2126	905

	Annual Increase (million)							
	Africa	Sub Saharan Africa	America	Latin America & Caribbean	Asia	South Asia	East Asia	EMENA
1990 - 2000	21.9	21.0	10.5	8.2	56.4	22.9	24.1	8.5
2000 - 2010	26.9	25.2	9.2	7.7	52.5	21.1	22.0	10.0
2010 - 2025	29.9	27.0	8.1	6.8	47.4	20.5	15.8	10.0
2025 - 2050	27.5	26.5	4.1	2.1	33.1	16.0	10.0	11.6

	% Growth Rates							
	Africa	Sub Saharan Africa	America	Latin America & Caribbean	Asia	South Asia	East Asia	EMENA
1990 - 2000	2.9	3.2	1.30	1.7	1.48	1.8	1.4	2.9
2000 - 2010	2.6	3.0	1.05	1.38	1.17	1.4	1.1	3.0
2010 - 2025	2.2	2.3	0.83	1.00	0.73	1.0	0.7	2.5
2025 - 2050	1.4	1.4	0.39	0.80	0.62	0.8	0.4	(2.3)

** EMENA - Europe,Middle East and North Africa.*
Source: World Bank.

Table 1.3. Estimated Food Availability (Kcal/Person/Day) for Selected Time Periods.

	1961-63	1969-71	1979-81	1988-90	Percent Change 1961/63-1988/90	Percent Change 1979/81-1988/90
World	2296	2434	2587	2697	17.5	4.2
Developing Countries	1939	2106	2319	2474	27.6	6.7
Africa	1995	2046	2148	2205	10.5	2.6
Latin America	2374	2514	2675	2689	13.3	0.5
Near East	2233	2398	2793	2924	30.9	4.7
Far East*	1966	2049	2185	2445	24.4	11.9
China	1701	2005	2323	2645	55.5	13.9
High-income countries	3063	3229	3333	3404	11.1	2.1
Western Europe	3086	3233	3371	3452	11.9	2.4
North America	3190	3370	3487	3603	12.9	3.3

Sources: Based on FAO data; Pinstrup Andersen in Global Perspectives for Food Production and Consumption, IFPRI 1992.
**Far East excludes China.*

Table 1.4. Number of Developing Countries with Average Food Availability Below 2,000 and 2,200 Kcal/Person/Day in 1961-63 and 1988-90.

	Number of Countries in Region	Number of Countries Below: 2,000 Kcal 1961-63	2,000 Kcal 1988-90	2,200 Kcal 1961-63	2,200 Kcal 1988-90
All developing countries	115	40	9	74	25
Africa	44	20	7[1]	36	18
Latin America	36	8	1[2]	18	3
Asia	27	10	1[3]	17	3
Oceania	8	2	0	3	1

Source: Per Pinstrup Andersen, IFPRI.
[1] Burundi; Central African Republic; Comoros; Mozambique; Rwanda; Sierre Leone; and Somalia.
[2] Haiti.
[3] Afghanistan.

Table 1.5. Increases in Grain Required to Meet Basic Needs of Populations 1985-2025.

		Increases in MMT		
Period	Global	LDCs	Africa	Asia
1985 - 1990	17.6	16.1	3.6	11.1
1990 - 1995	18.3	17.2	4.1	11.4
1995 - 2000	18.4	17.0	4.6	11.1
2000 - 2005	18.3	17.8	5.2	10.8
2005 - 2010	18.0	17.3	5.5	10.2
2010 - 2015	17.7	17.1	5.8	9.9
2015 - 2020	17.5	17.0	6.0	9.7
2020 - 2025	16.8	16.5	6.1	9.1

Sources: World Bank and author's estimates.

Table 1.6. Estimated Percentage Increases in Demand 1990-2050.

	Population				Income				Income Elasticity				Demand			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Less Developed Countries	1.9	1.6	1.3	0.8	2.9	3.1	2.7	2.7	0.4	0.4	0.3	0.3	3.1	2.8	2.1	1.6
Sub Saharan Africa	3.2	3.0	2.3	1.4	0.3	0.5	2.0	2.9	0.6	0.6	0.5	0.5	3.4	3.3	3.2	2.9
East Asia	1.4	1.1	0.7	0.4	5.7	4.6	4.0	3.9	0.2	0.1	0.1	0.1	2.6	2.1	1.8	1.0
South Asia	1.8	1.4	1.0	0.8	3.1	3.0	3.1	3.1	0.4	0.4	0.4	0.3	3.1	3.0	2.5	1.9
Latin America	1.7	1.4	1.0	0.8	2.2	1.7	1.4	1.0	0.8	2.2	3.0	2.2	2.2	0.3	0.3	0.3
MENA	2.0	3.0	2.5	2.3	1.6	2.5	2.5	2.5	0.3	0.3	0.3	0.3	2.5	3.4	3.2	3.0

Time Periods:

1. 1990 - 2000
2. 2000 - 2010
3. 2010 - 2025
4. 2025 - 2050

Sources: 1990 - 2000 Data Based on IFPRI.
2000 - 2050 Data Based on World Bank and author's estimates.

Table 1.7. Estimated Percentage Increases in Demand for Food, 1990-2050.

	1990-2000	2000-2010	2010-2025	2025-2050
Developing Countries	3.1	2.8	2.1	1.6
Sub-Saharan Africa	3.4	3.3	3.2	2.9
East Asia	2.6	2.1	1.8	1.0
South Asia	3.1	3.0	2.5	1.9
Latin America	2.5	2.0	1.3	0.8
Middle East & North Africa	2.5	3.4	3.2	3.0

Table 1.8. Growth Rate in Demand for Cereals in Developing Countries, 1960-2050.

Year	1960-70	1970-80	1980-90	1990-2000	2000-2025	2025-2050
All Cereals	3.6	3.9	2.5	3.3	2.3	2.2
Wheat	4.1	5.8	3.7	3.5	3.0	2.5
Coarse Grains	3.7	3.5	2.0	3.0	3.2	3.0
Rice	3.3	2.9	2.1	2.7	2.0	1.5

Sources: World Bank, FAO, CIMMYT, IRRI, TAC, and author's estimates.

CHAPTER II

Food Supply

2.1 INTRODUCTION

This chapter first examines the recent record of growth in food and cereal production. Thereafter it considers the sources of growth in output, recognizing the very substantial contribution made by increases in yields. This is followed by separate sections that look at the available supply of water and land, and the role of technology in increasing output. The overall conclusion is that yields will have to rise substantially in the years ahead to meet future demand.

2.2 TRENDS IN FOOD SUPPLY

The last 40 years have been characterized by remarkable increases in agricultural output in the world, especially in the developing countries. There have been substantial increases in production and improvements in nutrition over a time when there were gloomy predictions of wholesale famine and food shortages. These predictions, mostly made in the 1960s, were given credence by a combination of a reduction in production in the United States of America, crop failures in the former USSR, droughts in parts of Asia and Africa, and a failure of the sardine harvest off the coast of South America (further reducing supplies of animal feed stocks). The drop in global supply of food and subsequent sharp increases in global prices of staples came at a time when population increases seemed to be growing exponentially, heightening Malthusian-inspired fears about the world's ability to increase supplies in line with future demands. Since that time, however, the real prices of staples such as rice and wheat have dropped by between 35 percent and 50 percent.

FAO data show that there has been a steady increase in food production since 1960. In the developing countries as a whole, the long term trend has been upward with output of food and agriculture increasing at about 3 percent a year, a rate in excess of population growth, so that *per capita* outputs of both food and agriculture have been increasing [see Figures 2.1 and 2.2]. During the 30 years from 1960 to 1990, there have been substantial differences in per capita output among the different major regions of the world. The most striking contrast is between the paths followed by Asia and Africa. Per capita production in Asia started from a low point in 1960, and rose by nearly 40 percent by 1990; production in Africa was at a high level in 1960 but slow growth and a rapid increase in population led to a more than 25 percent decline in per capita output over the 30-year period.

Over the shorter run from, 1980 to 1990, both agricultural and food production have increased substantially [see Table 2.1]. Worldwide production rose by 25 percent and per capita output rose by 4 percent. Performance of the developing countries as a whole has been impressive over the decade, with output of agriculture and food production increasing by 40 percent or an average of 3.1 percent a year over this period. Per capita output rose by a healthy 13 percent, averaging close to 1 percent per year. Regional growth in the decade mirrored the longer-term trend over the past 3 decades. The highest growth rates in output have been in Asia, where China and India increased their output by more than 50 percent over the decade or by close to 3.5 percent a year, with per capita output rising substantially in both countries. In Sub-Saharan Africa however, while output grew by an average of 2 percent a year, this was at a lower rate than population growth, so that per capita output fell by 3 percent over the decade. Per capita output also fell in the Middle East and North Africa by about 4 percent as output grew by an average of 1.9 percent over the period from 1980 to 1990.

World trade in agricultural production has grown rapidly between 1980 and 1990. The developing countries supplemented their domestic supplies by increasing their imports by some 26 percent by value (in 1990 all agricultural imports in the developing countries were valued at $107 billion, roughly 16 percent of the estimated total value of their agricultural production) [FAO 1992]. Since 1980, *net* grain imports by developing countries have been 7 percent to 10 percent of consumption, rising from a 3.5 percent of total consumption in 1990.

In 1990, imports of foods exceeded exports of foods by $8 billion (though there was a trade surplus of $10 billion for all agriculture exports). Cereals, especially wheat and coarse grain, constitute an important component of food imports. These imports have been growing, rising from 68.8 million tons in 1974 to 113.3 million tons, or by 73 percent, in 1990 [see Table 2.2]. The biggest increases in imports, by volume, were in the Middle East and North Africa where the "oil boom" led to substantial increases in demand for wheat and coarse grains at a time when domestic production only increased very moderately. The next largest increase in imports was in East Asia, where rapid growth gave rise to added demand and to an increase in imports of wheat and wheaten products and grains for animal foodstuffs. There were also increases in imports in Sub-Saharan Africa, especially for rice and wheat as domestic production of local food-stuffs lagged behind demand. In contrast to the other regions, South Asia had a *decrease* in imports of cereals, as domestic supplies increased rapidly to satisfy national demands.

For the record, it should be noted that there are wide differences in the projections of the volume of imports of cereals in the future. The World Bank projects a net *deficit* in trade in cereals of 140 million tons in Asia by the year 2000; IFPRI projects a net *surplus* of 51 million tons for the same region; and FAO projects a net deficit of 19 million tons for the same region [Brown and Goldin 1992]. The main reasons for these wide spreads lie in the difference of views about the future policies that will be followed by China and the capacity of China to increase its domestic production in the years ahead. There is general agreement, though, that imports into the Middle East and Sub-Saharan Africa will rise over the years ahead as domestic production lags and demand grows for wheat and rice in areas where these commodities cannot be produced [Brown and Goldin 1992].

It should be noted that imports — though they have grown rapidly — are still a small part of the total supply of cereals in the developing countries. For the purpose of estimating needed domestic supply, it is assumed in this paper that imports of cereals, especially rice, will not grow substantially in volume in the years ahead. Governments will look to domestic supplies to provide most of their basic staples, as they do at present.

The increases in supply and food production in the developing countries as a whole have been substantial. Historically, output of food has kept pace with demand in all regions except in the Middle East and Africa, especially Sub-Saharan Africa. If the rate of increase in food production of the past decade (3.0%) can be sustained, it would be adequate to meet the demand projections for the developing countries made in the first part of this paper. By the same token, if the past rates of increase in Sub-Saharan Africa (2%) and in the Middle East and North Africa (1.9%) continue, output will lag well behind demand projections of 3.4 percent and 2.5 percent respectively, up to, 2000 and the year beyond that.

2.3 CHANGES IN SOURCES OF GROWTH

The recent increases in production in the developing countries have been accompanied by a fundamental shift in the sources of agricultural growth. Prior to the 1950s, most of the increase in agriculture and food production came from bringing additional acreage into production. As population increased more land was brought under production. Land extensive techniques of production, such as shifting cultivation with reliance on land rotation to restore the fertility of the soil, were widely practiced. Farmers in most developing countries used little in the way of purchased inputs and yields per acre were low. Since the 1950s, however, rising yields per acre have become a more important source of increase in output than expanding acreage. A recent IFPRI study estimated that 70 percent of the increase in major food crops between 1960 and 1970 could be attributed to yield increases and 30 percent to an expansion of area. During the next decade, 1970-1980, the ratio showed an even larger proportion of output, some 80 percent, coming from increased yields and only 20 percent of the increase in output coming from expanded acreage [Paulino 1986]. In a separate study in 1992, the World Bank estimated that 92 percent of the 118 percent increase in cereal production in the developing countries came from increased yields, and only 8 percent could be accounted for by an expansion of area under production [World Bank 1992].

The World Bank analysis showed that the greatest change in sources of growth came from East Asia where average yields in 1989 to 1990 were higher than in other regions (3.7 tons per ha), and that all but 6 percent of the increase of cereal output since 1961 to 1963 could be explained by increases in yields. In South Asia, 86 percent of the increase in output came from increases in yields, even though average yields were relatively low (1.9 tons per ha). In Latin America 71 percent of the output came from increased yields and the average yields were 2.1 tons per hectare; 77 percent of the output of the Middle East and North Africa was attributable to yield increases with average yields being 1.4 tons per ha. Sub-Saharan Africa, with yields of 1 ton per hectare, relied most heavily on expanding acreage for increasing output, with close to half of the growth in output coming from this source [see Table 2.3]. On a commodity basis, almost all of the increases in wheat and rice production in the 1980s came from increased yields while, in the 1970s, about 70 percent of the increase in corn products was attributable to yield increases (see below).

The historical and continuing shift from land-extensive agriculture to intensive agriculture is similar to the process of agricultural development that has taken place in many Western European countries and in Japan. The increasing modernization of traditional production systems involved the agriculture sector becoming increasingly dependent on "inputs" from off the farm. The process itself has been characterized as one that shifts from "traditional" (no external inputs) to "moderate technological" (continuous cropping with some chemical fertilizers), from "highly technological" (using more fertilizers and some mechanization) to "specialized technological" (fully mechanized, heavy applications of fertilizer and pesticides) [Buringh 1989]. Modernization, as described above, depends increasingly on external inputs, and on the discovery and development of cost reducing technologies in the manufacturing sector for use in the agricultural sector, as illustrated by the progress made in the chemical fertilizer industry. Many of the external inputs are based on fossil fuels, so that the development of agriculture will not be immune to the availability of oil based products and the vagaries of the oil markets in the years ahead. Indeed, some see this as a major obstacle to the long-term development of agriculture [Pimentel 1989].

Each phase of modernization leads to greater integration of the agricultural sector into the national economy and the world economy. Government policies and programs can either accelerate or hinder the process. In recent years, more benign policies, especially in Asia, and a substantial increase in investments in infrastructure, including irrigation, have facilitated the process of modernization. There has also been an expansion of services to support agriculture, including research, extension, credit, seed distribution, and distribution of fertilizer. In addition, as is stressed throughout this chapter, a most important contribution to yield increases has been the development and diffusion of yield-increasing technologies embodied in the high-yielding varieties of cereals, notably rice and wheat.

Future increases in output will have to come from the same sources as in the past with an even greater emphasis on yield increases. In addition, there will have to be greater concern about "sustainability." Sustainability can be defined in technical or economic terms or on the basis of community values [Ruttan 1991]. The most widely accepted definition, however, is that adopted by the Brundtland Commission: "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [World Commission on Environment 1987].

This broad definition does not provide any guidance as to how this highly desirable goal should be fulfilled. In the past there has been sustainable agriculture based largely on forest and bush fallow systems that functioned effectively because of the plentiful supply of land and the low population density. However, these low productivity systems broke down as population pressures grew and pressure on the land led to soil degradation when fallow periods were shortened without any replacement of lost nutrients.

The earlier sustainable systems were low productivity systems, that could only provide food and employment for limited numbers. The subsequent modernization of agriculture and the introduction of purchased inputs have certainly met the test of providing for the present. The best evidence of the success of "modern" agriculture in the tropics is to be seen not only in yield increases but also in the consistent long-term decline in wheat, corn and rice prices. Rising productivity has been able to supply for the increasing demand of growing populations without any substantial increases in real prices [World Bank 1992].

Despite the successes in increasing output, there are a number of concerns about sustainable production in the future. The very process of modernization, with the increased use of agrochemicals and the intensification of land use, is having deleterious effects on the resource base. Spillover effects from intensification of land use include soil degradation; waterlogging and salination; surface water and groundwater contamination from plant nutrients and pesticides; resistance of insects, weeds and pathogens to present methods of control; and the loss of land races and habitats. Where production systems expand into more fragile areas, there is further resource degradation, including soil erosion, deforestation, species loss and degradation of water quality [Ruttan 1991].

In addition to the concerns about sustainability there is also some concern about the prospects for increasing yields and output to meet future demands. Future increases in output to meet projected demand will have to come from the same sources as in the past, but with an even greater emphasis on yield increases. There are misgivings about the availability of suitable land and adequate water supplies in the developing countries to meet future requirements. There is also a question about whether the technology that has provided such a stimulus for increasing yields in the past can continue to provide the growth of yields that will be needed in the future. An important issue is whether "diminishing returns" are setting in and whether other technologies will be available to lead to sustainable growth in the years ahead. These issues are intertwined but are discussed separately below.

2.4 THE SUPPLY OF WATER

This section examines whether the available supplies of fresh water will be adequate to meet future demand. The first part looks at the supply and regional distribution of fresh water. The next part looks at the growing pressure on supplies, especially in the Middle East and Africa and points out that Pakistan may be at risk by 2025. Thereafter, there is a consideration of the need for a "holistic" approach to managing the demand for water with supplies being freed for use in urban and industrial areas through increasing efficiency of water use in agriculture. The case of Israel demonstrates the possibilities in this area.

2.4.1 The Availability of Water

Water, "the lifeblood of the biosphere," is one of the most abundant resources of the globe. The greatest quantity of this resource (97%) exists in the oceans; the second largest amount (2.2%) exists as ice and snow in the polar regions and only about 0.7 percent of the total water supply is usable fresh water that, inter alia, sustains the world's agricultural system. Fortunately for mankind, even though the supply of fresh water is finite in quantity, it is a "renewable resource" so that the supply is continuously replenished.

Each year the sun's energy evaporates some 500,000 cubic kilometers of moisture, mostly off the oceans, that enter into the atmosphere and then fall back on the globe as rain, sleet, or snow. This process transfers about 40,000 cubic kilometers of moisture a year from the oceans to the land. After falling to the earth, the moisture is recycled. Most of it returns to the atmosphere from the surface of the earth as it evaporates from moist surfaces and water bodies, or after being consumed by plants it returns to the earth through evapo-transpiration. The remaining water seeps into the soil and replenishes subsurface aquifers, and much of it eventually finds its way into rivers, lakes and to the sea, and so back into the hydrological cycle [Falkenmark & Wildstrand 1992]. This process may be rapid or it may take years [Hillel 1991].

Most climatologists and hydrologists agree that there is no natural process, short of climate change, that can increase the world's fresh water supply. If global temperatures were to rise on a sustained basis, then there would be an increase in the evaporation of water from land and water surfaces. The greater the warming, the larger the expected increase in precipitation. One "simple level of analysis" suggests that global warming of about 30 degrees Celsius could well lead to an increase in evaporation of about 10 percent, and to an increase in average global precipitation of around 10 percent [Gleick 1992]. However, if there was global warming due to the greenhouse gas buildup, temperature changes would be unevenly distributed with the biggest increases at high latitudes and lower increases closer to the equator; this in turn would affect the timing, duration and distribution of rainfall in these regions [Mintzer 1992].

There is a great deal of uncertainty about the extent of global warming and whether the buildup of carbon dioxide in the atmosphere is accelerating, as well as about the complex interactions between rising temperatures, changes in climate, and changes in rainfall. However, the *possible* effects of changes in the climate on water supply make it important that all concerned with improving the management of the world's water supply support continued research and inquiry into the subject. In the near future though, it appears unlikely that there will be any significant changes in the total supply of fresh water due to global warming.

There are man-made processes for increasing the supply of fresh water. One of the most important of these is the conversion of saline water in the ocean into fresh water by removing salts through desalination or by filtration. Thus far, however, the processes that have been developed for this purpose are highly energy intensive and costly; the plants presently in operation are mostly in the "oil rich, water poor" nations of the Persian Gulf. It is estimated that there are more than 7,500 desalting plants operating worldwide, but together, they only produce one-tenth of one percent (.01%) of the world's total fresh water use [Postel 1992]. Presently, the cost of production of this water ranges from ten to twenty times the amount that farmers are paying for water supplies. As a result, desalinated water is produced almost exclusively as potable water for human consumption. Without substantial progress in lowering the cost of power generation, this form of desalination will continue to have little impact on increasing the total supply of fresh water in the world. In the past the great hope was that low cost nuclear power could provide the energy for cheap, desalinated water; however, this hope has not been realized. Whatever the technology, it is most likely that desalination will continue to be used to provide potable water in selected areas. Its role in irrigation will be very limited, and will probably be confined to aiding in the production of selective high unit value crops such as horticultural crops and special ornamental crops [Postel 1992].

2.4.2 The Distribution of Water Availability

The global supply of water is unevenly distributed. The amount of renewable fresh water that passes through the aquifers and rivers of a country is determined to a large measure by that country's place in the global water cycle. Generally, the driest areas are in the transition regions between the tropics and temperate climates (latitudes of about 20 to 30 degrees north and south of the equator). At these latitudes dry, cool air that is transferred from the atmosphere above the equator falls from the upper atmosphere, leaving little moisture for precipitation in these areas. At the national level, the indigenous water supply, produced locally from rain or snow, may be complemented by exogenous supplies produced from rain and snow elsewhere and carried into a region by transnational rivers or groundwater systems [Falkenmark and Wildstrand 1992].

The combination of uneven distribution of water and rapidly expanding population is putting increasing pressure on available water resources in a number of countries. In this context, hydrologists often designate the status of countries by the ratio of population to flow units of water, where one flow unit equals 1 million cubic meters per year. If the population per flow unit is low, below 100, water supply does not seem to be a problem. As the water supply per capita lessens, especially when there are more than 600 persons per flow unit, then signs of stress appear and water is used very efficiently [Falkenmark and Wildstrand 1992]. By these measures, there is ample water in South America, Sub-Saharan Africa and most of Asia. North Africa and the Middle East, however, are experiencing water stress situations that will worsen substantially by 2025. The situation in Sub-Saharan Africa will also deteriorate in the future.

Another very informal but instructive "yardstick" of water availability, based on the World Bank experience, is that "when available water resources are between 1,000 and 2,000 cubic meters per capita per year, large investments are generally required to meet water demand. However, when water resources are below about 1,000 cubic meters per year, it takes difficult socioeconomic adjustments to cope with such scarcity" [World Bank 1992]. In 1990, by one count, eighteen countries had water availability of less than around 1,000 cubic meters per capita and nine of these countries, all in the Middle East, had a water availability of less than 500 cubic meters per capita [Gleick 1992]. By 2025-2050, an increasing number of countries would be facing "difficult socio-economic adjustments" to cope with water shortages. Most of these countries are in Africa and the Middle East [see Table 2.4]. Fortunately, *by this count* the two most populous countries in the world, China and India, appear to have an ample supply of water to meet their future needs; *however by 2025, Pakistan, one of the major users of water for irrigation, will be facing shortages (and needs to start planning now on how to use its water resources more efficiently than hitherto).*

The regions under greater stress at present are the Middle East and North Africa. The vulnerability of these regions is shown by a shortage index, or the ratio of demand for water (withdrawals) to available renewal of supplies [Gleick 1992]. Nine out of twelve countries in the Middle East use more than 100 percent of the domestic renewable water supply. This is either because their domestic water supply is low or because demand is high, or a combination of both. These nine countries depend on imports of fresh water, extraction of groundwater at a nonrenewable rate, and high cost desalinization of nonpotable water for part of their supply of water. These countries include Egypt, a country that depends on irrigation for all of its domestic production of food, as well as oil-rich countries such as Saudi Arabia that can afford to import its food.

Population per flow unit of water is a macro indicator of the relationship between population and water and, as such, reveals nothing about the location of populations and the available supply of water. Thus, while India and China have ample supplies of water relative to population at a macrolevel, there are many localities where demand is putting pressure on the existing supplies. This relative scarcity is manifested in many ways including falling water tables and rising costs for water. Locational mismatches between supply and demand are leading to increasing competition among different groups for supplies that are available.

One of the issues that will loom larger in the years ahead is the competition for water resources between urban and industrial consumers and the agricultural sector. Urbanization is proceeding very rapidly and is expected to increase by 2.5 billion people by 2025, when 60 percent of the population in developing countries will be urbanized, many living in an increasing number of "megacities." One rough estimate is that each additional million urban dwellers will require the same amount of water for domestic purposes as is needed to irrigate 10,000 hectares of land [Hillel 1993]. On the face of it, this degree of competition does not appear to be a serious problem, although 10,000 hectares would represent 10 percent of the irrigated area in a country like Jordan. In fact, there are already signs of stress in different parts of the world where large urban centers have expanded rapidly (and are continuing to expand), and are competing with agriculture for available water supplies. It is likely that problems of competition will increase as urban populations grow. The increase in urban dwellers by 2025 would require the same amount of water needed to irrigate 25 million hectares or around 15 percent of the total irrigated area in the developing countries. This is a substantial proportion of irrigated land. What is not known is whether the competition for water will be confined to the immediate hinterland of the large urban conglomerations or whether the competition will extend much further afield and, if so, what the impact will be on the development of irrigated agriculture.

The increasing pressure on available water supplies will inevitably require more efficient use of water resources in agriculture, the largest user of water. Globally, some 69 percent of the annual withdrawal of fresh water is used for agriculture, 23 percent is used for industry, and 8 percent for domestic use [WRI 1992]. In Africa, Asia and South America, agriculture "withdraws" 88 percent, 86 percent, and 59 percent of the water supplies (this compares with 33% in Europe). In the Middle East and North Africa, the area of greatest water shortage, the agriculture sector in eleven out of the fourteen countries in the region uses more than 80 percent of the available fresh water supply, and in nine of the countries the agriculture sector uses more than 90 percent of the available water supply [author's estimate].

A relatively small percentage increase in the efficiency of water use in the agricultural sector can contribute substantially to meet the growing demands for water for municipal and industrial use. In typical "traditional" irrigation schemes, as little as 30 percent of applied water may be used for crop evapotranspiration. Modern schemes using techniques such as drip irrigation, on the other hand, achieve efficiencies of around 65 percent. In a typical situation where 80 percent of the total water is used for irrigation, a 10 percent increase in the efficiency of irrigation would provide 50 percent more water for municipal and industrial use [Hillel 1993]. Any such transfer of water, though, would require a holistic approach to the management of the overall demand for water.

In this general context, the current and growing water shortage in the Middle East and North Africa demonstrate the need for a more holistic approach to water management in the future. The general consensus is that there are limited prospects for low cost supply enhancement in the Middle East, and that the most effective way of meeting future demand is by managing scarce water supplies more effectively. Managing scarce water supplies will involve improving urban delivery systems, improving the regulation of groundwater, and making better use of industrial waste water. By 2020, it is expected that 40 percent of the municipal and industrial waste water in Israel will be recycled and more than 90 percent of the country's irrigation will be with recycled water [Hillel 1993].

Demand management is conservation oriented and is intended to influence consumer behavior by introducing incentives (or penalties) so that consumers will use water more efficiently than in the past. Demand management can take many forms, including the rationing of water or the use of market pricing mechanisms. While rationing is an option, the use of water charges, subject to market forces, is usually seen to be a more effective means of improving efficiency of water use and for allocating water both intersectorally and intrasectorally, from low value use to higher value use. Establishing an effective market for water, however, requires a suitable legislative framework protecting riparian and water rights as well as having a monitoring system to ensure that the market is functioning effectively.

The case of Israel is instructive. Limited water supplies have been used effectively to raise on-farm productivity, and ensure more efficient use of moisture. Between 1950 and 1990, the area under irrigation expanded from some 30,000 hectares to 213,000 hectares while production per hectare increased eight-fold, and the yields per unit of water increased from one kilogram per cubic meter to about 2.5 kilograms per cubic meter [Hillel 1993]. The Israeli experience confirms the importance of a holistic approach to water issues (as urged by the UNCED Conference), as well as a sector-wide approach within agriculture (for example, joint irrigation and agronomic research to get maximum returns from water). In addition, Israel, with a rapidly growing nonagricultural sector, has made good use of recycled waste water for agriculture. The increasingly sophisticated means of irrigation that are in vogue in Israel, and which will probably be used throughout most of the Middle East in the future, are too costly for producing bulky, low unit cost foods. Therefore, in times to come, the agriculture sector will have to become more specialized, relying on production of high unit value crops for export and increased food imports.

There are many localized situations of water shortage. In some areas, water tables are said to be falling as increasing numbers of uncontrolled wells draw down available groundwater. This has certainly taken place in some aquifers, consisting of nonrenewable water supplies. It is very difficult to establish the extent of this phenomenon; there are few longitudinal studies that measure changes over time, covering years of ample rainfall as well as years of sparse rainfall. Increasing costs of drilling and withdrawing water from some aquifers are indicators that water tables are falling. However, the state of knowledge is such that this subject urgently needs examination, especially in the areas where there's been a rapid spread of tubewells.

A further issue of significance regarding the availability of water is the extent of reliance of countries on exogenous sources of water. There are a number of countries that depend on river flows that emanate outside their borders for at least one-third of their water supplies. The number of countries involved highlights the importance of the Danube, Nile, Mekong, Euphrates and Tigris rivers, all of which provide water to more than one country so that the irrigation systems in a number of countries depend on the effective functioning of international treaties. Future development is contingent on agreed-upon policies for allocating international water resources among nations competing for the use of these waters. The need for such policies is inhibiting the development of water resources in Africa, where a handful of rivers are contiguous to at least 22 countries. Similarly, the issues involved in sharing the waters of the Jordan River are extremely problematic. Whatever solutions are envisaged, whether pipelines from the Nile or pipelines from Turkey transporting water to the region, they will require unprecedented cooperation among different nations. While this may seem problematic, the precedent of the division of the Indus waters between India and Pakistan may well point the way in the future.

In conclusion, it appears that there is no global shortage of water, as such, but that the pressure of increasing population is already causing problems in semi-arid regions such as the Middle East and North Africa. Since the water supply is finite, increasing population growth and urbanization will inevitably add to the pressure for reducing wastage of water, especially in irrigation, by far the largest user of water. Over the longer run, governments will have to develop a more comprehensive approach to water planning than is presently the case. This will have to include greater emphasis on the management of demand for water, as well as improving the efficiency of water use within the various sectors, especially in agriculture.

The ample availability of water may mask seasonal shortages, (e.g., Bangladesh, one of the countries with the largest per capita water availability, has a dry season when water is relatively scarce). Similarly, it should be noted that the availability of water does not necessarily mean that there is unlimited scope for expanding the area that can be irrigated. There is a limit to the potentially irrigable area based on the complementarity of land and water and the costs of developing whatever potential does exist. Despite the fact that most of Asia has ample water supplies, it appears that the current rate of expansion of irrigation is not sustainable beyond 2025 [see Chapter IV].

2.5 THE SUPPLY OF LAND

This section considers whether shortage of land will be a constraint to agricultural production in the years ahead. The first part looks at the supply of land and the potential for expanding the area under crop production. Thereafter, there is consideration of the competition for land from urbanization, and constraints arising from the loss of land due to soil degradation. This section also reviews the distribution of the potentially productive land, and considers the obstacles to these lands being brought into commercial production in the near future. It appears that while there are opportunities for expanding the area under cultivation in some parts of the world, the major increases and output of the future will have to continue to be from increased yields.

2.5.1 The Supply of Agricultural Land

There is a great deal of ambiguity about the extent of land that is suitable for crop production, but is either unused or used for other purposes. The caveats regarding many and all estimates of land resource availability are best illustrated by the following quotation from one of the world's foremost authorities on this topic:

> "A problem with all global assessments, calculations and projections on land and its related aspects is that they cannot be currently verified. All data on land use, land productivity, degradation and losses of land, for example, contain inaccuracies because in many countries no reliable statistics are available on land and soil. Data presented by international organizations like the Food and Agricultural Organization (FAO) are often based on estimations, but they are used by researchers because they are the best available. The problem of reliability of the information used becomes evident when computers analyze data and identify the various discrepancies. For example, a discussion on the land area of the world that is suitable for agricultural production depends on the soil map of the world. This provides the best information available; however, only one-quarter of the land area is covered by real soil surveys and the rest is based on scarce information picked up during various tours. Moreover, no uniform definitions are given for many land and soil resources in world statistics. For instance, when is an area covered by grass and trees considered pasture? And when is it forest land? This not only depends on the definitions for both types of land use, but also how such definitions are interpreted. Statistical data and information on maps are often used to support political situations. Thus, some countries present data specifically adapted for political reasons." [Buringh 1989.]

Bearing the above in mind, FAO estimates that the total land area in the world covers around 13 billion hectares; 7 billion of these are in the developing countries. Around 2.1 billion hectares in the developing countries are under forest and wood lots; a further 2.1 billion hectares are under permanent pasture; 770 million hectares are used for agriculture with 72 million hectares being under permanent crops. The remaining 2.5 billion hectares are classified as "other land" and includes areas covered by polar ice caps, deserts, and inaccessible and unusable mountain areas as well as land taken up by the spread of urbanization. Based on FAO data only 11 percent of the land area in developing countries is used for crop production, and around 60 percent of it is either in forest and wood lots, or under permanent pastures.

The frontiers of production have expanded over time. As populations have increased, the area cultivated has also grown. Over the past 100 years, an additional 500 million hectares of land have been brought into cultivation largely at the expense of forest land. This expansion in cultivated land represents a rise from 7 percent of the earth's land area to 11 percent [Buringh 1992]. At the present time, there is a steady, continuing expansion of land being brought into cultivation; between 1975 and 1990 an additional 46 million hectares in the developing countries were brought under cultivation, mostly by converting forest and woodlands into crop land. This represented a 6 percent increase over a 15-year period, with the largest increases being in South America (10%) and Africa (5%). During this time, too, there was a rapid expansion of conversion of forest to pasture land, especially in South America [WRI 1992].

There are a number of estimates of the extent of the nonarable land that has potential for crop production. A recent estimate has been made by the World Bank, relying largely on the work of

Buringh and Dudal [P. Crossen and J. Anderson 1992]. This study classified land by use: crop land, grassland, forest land, and nonagricultural uses that included urban, polar ice caps, and so forth. These lands have then been subdivided into high, medium and low potential crop land based on the information available about soil and climatic conditions prevailing in major regions around the world. In this analysis the potential, whether high, medium or low, has also been based on possibilities using current technology under prevailing levels of farm management. These estimates of potential, and estimates they are, indicate that there is substantial scope for expansion of land that could be used for crop production [see Table 2.5]. It should be noted that other analysts are less sanguine about the quality of these "unused" lands, but they all agree that there is substantial untapped physical potential for increased production [Dregne 1988].

The World Bank analysis indicates that the world's crop land can be doubled with roughly half of the putative crop land having more than high or medium potential, and half having low potential. It is the potential of this unused and underutilized crop land now in grasslands, woodlands or forests, that is the basis for some of the projections that the global food supply could be increased to provide food enough for 9 billion people without any substantial changes in technology. Most of this potentially usable crop land is in the developing countries. Indeed, it is estimated that nearly 90 percent of this potential crop land, more than 1.3 billion hectares are in the developing countries, and almost 95 percent of this is in Africa and South America with the remaining 5 percent being in Central America, and in the Middle East. *Significantly, the potential for expansion of area in Asia is extremely limited* [Table 2.5].

2.5.2 Constraints to the Supply of Land

It appears that there is ample scope for the horizontal extension of agricultural production other than in Asia. There are constraints, though, that will limit the extent of the land available for future crop production. There will also be competing demands for land from urbanization. In this regard, though, it is estimated that the projected increase in urban population will require less than 0.001 percent of the potentially cultivable land in the developing countries (and 0.5% of the potentially cultivable land in Africa and South Asia). By this measure, urbanization will have a selective but largely marginal impact on land availability for agricultural production [Buringh 1989].

Land degradation is also a constraint on the expansion of production in potentially usable areas of the developing countries. Land degradation in all its forms includes losses from desertification, salination, and soil erosion. Degradation covers everything from the "mild" destruction of soils, which can be recovered easily, to catastrophic conditions in which land is so badly damaged that it is no longer suitable for agricultural activities, and must be permanently abandoned.

There is abundant anecdotal evidence about land degradation helped along by the fact that extreme forms of erosion and salination are visible to the naked eye. But visible degradation can be misleading, as revealed by the recent reassessments of the "march of the desert" in the Sahel region of Africa where, following the end of a long dry spell, satellite imagery showed that vegetative cover had returned to large areas that were formerly classified as totally degraded [Yudelman 1991].

Nevertheless, degradation appears to be most serious in Africa. It is estimated that as much as 22 percent of the region's vegetative cover is degraded (494 million hectares). However, only around 1 percent of the degraded area (5 million hectares) is considered to have suffered extreme degradation (the point at which it had lost its productive value); 24 percent of the degraded area or 124 million hectares are listed as being "strongly degraded," and recoverable only at high cost. The remaining 366 million hectares or 75 percent of the area classified as degraded, is considered to have "light or moderate" damage that can be reversed by changes in land use practices. Thus, the overall picture that emerges from this source is one of widespread degradation, but only about 4 percent of the total vegetative area is seriously degraded, with 18 percent being lightly degraded and recoverable through changes in farming practices [WRI 1992].

The analysis pinpoints overgrazing by livestock as the single most important source of degradation (49% of land degradation in Africa, and 35% worldwide). Deforestation, land clearing activities, and unwise agricultural practices also contribute to temporary and, in some cases, permanent destruction of the soil. In many instances, the root cause of the spread of land degradation has been that land-extensive systems of agricultural production and cattle rearing, that were ecologically sound when there was a favorable man-land ratio, are continuing even though this ratio has been disturbed. Land formerly left fallow for several years to regenerate is being used more intensively without the benefit of improved technologies, especially soil enhancing inputs such as lime, fertilizers, manure and mulch. Increasing cattle herds are continuously grazing on less acreage each year, destroying the vegetative cover with resulting erosion.

Soil salinity and waterlogging of soils are important causes of land degradation and destruction of the soil's productive capacity. Salinity can arise from natural causes (e.g., ocean water intrusion into streams and aquifers), or from irrigation. In some areas, the primary or natural salination is substantial (e.g., in Northern India). In general, though, irrigation-induced salination is considered to be an important reason for this form of environmental degradation. Salination occurs because there is excess irrigation and deep percolation of water in areas that have poor drainage. With the passage of time, the water table rises carrying the dissolved salts in the water close to the surface. Excess salinity within the root zones reduces and suppresses plant growth and a high enough concentration of salts can be lethal to plants, leading to the eventual abandonment of agricultural lands.

The buildup of salinity is a long, degenerative process and it may take 15 to 20 years to appear after the introduction of irrigation. Since it takes years before salinity is clearly injurious to plant growth, there is little monitoring for its presence by irrigation authorities. This general lack of monitoring of salinity-affected areas has contributed to the lack of field-level information on this topic. In addition there are no standardized definitions of what constitutes salination; some countries categorize salination as "light," "moderate" and "heavy," leaving it to the judgement of officials concerned to determine the extent and seriousness of the soil degradation. Furthermore, salination is a recurring phenomenon so that areas that appear to be saline during one year may appear to be productive in another year.

The estimates of soil salinity vary greatly, so much so that it is difficult to be definitive. A recent World Bank survey indicated that 3 percent of India's irrigated areas are saline [Umali 1992]. But this view appears to be inconsistent with the views of one of the leading authorities on salination in India, who has stated that there has *never* been a salinity map made for the Indian subcontinent and that at least *5 percent* of India's "most productive land" has become unproductive solely because of irrigation-induced salinity [Abrol 1987].

The best that can be said is that salination is a serious problem, especially in the drier areas that include close to 80 million hectares of irrigated land. In these areas larger quantities of irrigation water are used than elsewhere, and so a larger amount of salts are supplied. At the same time the quantity of rainfall available to leach away the accumulating salts is less than elsewhere. Salination is said to be spreading and some estimates are that 2 to 3 million hectares per year are lost due to this form of degradation. Since irrigated area has been expanding at roughly the same rate, this would imply that there is no net gain in productive land that is irrigated (although there are major programs in Pakistan and Egypt that are recovering saline lands, albeit at a high cost, probably in excess of $1,000 per hectare).

Land degradation in all its forms is spreading. The rate at which it is expanding is unknown; nor is much known about the effect of degradation on overall agricultural productivity [Oldeman 1993]. Much of the degradation, though, is heavily concentrated and is leading to land being abandoned in some areas. Over time, as population pressures increase, degradation will probably worsen unless steps are taken to correct the present causes of the problem. These include rationalizing the livestock industry, and modernizing the farm sector including the improvement of the operation of irrigation systems. It is unlikely, though, that the continued degradation of the natural resource base will be a major factor in limiting the extension of agricultural production, though this extension may well contribute to the degradation of the natural resource base.

The crude estimates of land availability and possible losses of land due to urbanization and land degradation show that there is a potential for doubling the area under cultivation in the developing countries. Most of this potential is in tropical Sub-Saharan Africa and South America. But there are other natural and man-made obstacles to the exploitation of this potential, most of which is in the tropics. One such obstacle is the presence of diseases. It is estimated that as much as one-third of tropical Africa, which might otherwise have been cultivated, remains largely unexploited because of the prevalence of tripanomisias. Tripanomisias affects both human beings and livestock. Population in the affected areas is sparse, and an absence of animal-drawn equipment inhibits the expansion of production as producers are confined to using hand-held equipment. So far there has only been limited progress in containing this debilitating disease. Other diseases have also inhibited the spread of human settlement in these tropical areas. There has been progress in controlling river blindness and guinea worm which have limited the use of substantial areas in West Africa, but other diseases such as chagas disease in tropical Latin America continues to act as barriers to expanding cultivation.

Another constraint to the expansion of cultivation is that the soils in large areas of the tropics are of poor quality, and deteriorate very rapidly when cultivated unless they are treated with fertilizers or lime. As a result, the expansion that has taken place in the tropical areas has left large areas of potentially cultivable land in a poor state, suitable only for raising livestock. Yet another obstacle centers around rights to land. There are a myriad of issues covering the rights to "ownership" and use of land in potentially cultivable areas in Africa and Latin America. These include the rights to communally-held property, and rights of indigenous and tribal people — and settlers — to occupy much of what appears to be "empty" land. These issues will slow down the expansion of cultivation in many parts of tropical Africa and Latin America.

There are economic barriers that inhibit the expansion of cultivation in the remoter parts of land-rich economies such as Zaire, Angola or tropical Bolivia. These areas are poorly served by highways and railroads. Moving goods in and out of these areas is costly, and high transport costs are a major obstacle to development. In addition, the cost of land clearing and settlement in tropical areas has turned out to be much higher than expected. This applies to areas as diverse as the outer islands of Indonesia, and the tropical lowlands of Peru.

The broad conclusion is that there appears to be a substantial area of underutilized land in Africa and Latin America that could be used for raising crops, but are yet to be exploited. However, there are significant natural and man-made obstacles to expanding the area under cultivation in many of these areas. The necessary conditions are not in place for rapid, low cost expansion in most of tropical Africa, though they are in place to a much greater extent in tropical Latin America.

Hypothetically, there is ample land in the world to provide for more than double the world's population even though most of these lands are in areas that lack basic infrastructure. If food prices were to rise sufficiently, there would be increased investment to produce food in these high-cost, marginal areas. By the same token, if food prices were to rise relative to the prices of other agricultural products (fibres and beverages) then the food supply *could* be doubled by converting that half of all the arable land now used for growing nonfood crops to producing food crops!

If recent history is any guide, it is probable that between one-third and one half of the increase in crop production in Latin America and Africa will come from expansion of area under cultivation, with increases in yields from land already under cultivation providing the remaining output. In Asia and the Middle East, land constraints are severe and there are only very limited opportunities for expanding the area under cultivation. For the foreseeable future, it appears that more than 90 percent of the increases in production in these areas, especially food crops, will have to continue to come from high yields.

2.6 TECHNOLOGY AND YIELDS

This section considers the technological changes and increases in yields that have taken place in the developing countries in the post-war era. It looks at the "breakthroughs" in plant breeding and their impact on increasing average yields. Thereafter, there is a brief consideration of the role of agrochemicals in increasing yields and a review of the spread of the modern high-yielding varieties. This section concludes by emphasizing the success of raising yields of the major cereals over the past 30 years as a prelude to discussing whether these high growth rates can be sustained in the future.

2.6.1 The Application of Science to Agriculture

The increases in yield, especially of cereals, has been described as part of the "greatest agricultural transformation in the history of human kind and most of it has taken place during our lifetime. The change was brought about by the rise of science based agriculture which permitted higher and more stable food production, insuring food stability and security for constantly growing world population" [Plucknett 1992].

Modern science-based agriculture had its origins in research on agricultural chemistry and plant nutrition and in the rediscovering of Mendel's laws of genetics. In more recent times, the evolution of increasingly selective chemical and organic pesticides has helped control plant diseases, weeds and insects. During this period there were great contributions by chemical and engineering industries which were able to capture the "economies of scale" and lower the costs of nitrogenous fertilizers and pesticides.

Arguably, the most successful illustration of the "application of science" to agriculture can be seen in the increase in average yields of corn in the U.S.A. For seventy years between the 1860s and 1930s, corn yields averaged around 1.4 tons per hectare. By 1990, average yields had increased more than fourfold to about 7 tons per hectare (and are still rising). While many social and economic factors influenced farmers "decisions," the increases in yield would not have occurred without 'science-based' technological changes arising from the development of high-yielding hybrid seeds, the growth of a dynamic seed industry and the widespread use of agrochemicals, including fertilizers and pesticides.

The application of science to agriculture in developing countries has been very much a post-World War II phenomenon. The great technical advances that have been made follow the same general pattern as those in the corn industry in the USA. The agricultural advances were made possible, in large part, by scientists working in national agricultural research centers in developed and developing countries, especially in India, China and Mexico, as well as in the international agricultural research centers that are part of the Consultative Group for International Agricultural Research (CGIAR). The technological advances involved the discovery, development and diffusion of high-yielding varieties of wheat and rice (and to a lesser extent corn), that have broken through traditional yield limits and permitted a quantum leap in yields when used with appropriate inputs of fertilizers, pesticides and water.

The main characteristics of the modern high-yielding varieties of wheat and rice are that they are so genetically altered, by traditional methods of plant breeding, that they have a semi-dwarfed stature with a short sturdy stem which is able to support a large full head of grain when exposed to wind and rain. In contrast with long-stemmed predecessors, they have a high response to fertilizers and can convert large amounts of fertilizer into grain without lodging. The breeding programs for corn have followed a different route but have led to the development of improved germ-plasm that also incorporates improvements in yield potential.

The initial improved varieties of rice, wheat and corn have been constantly improved over the ensuing years. Successive generations of varieties have been bred to incorporate desired qualities; shorter maturation dates (to provide opportunities for double or even triple cropping), improved resistance to diseases and pests, and improved characteristics for processing and cooking as well as some adaptation for different environments. The major achievements in plant breeding have come about by increasing the ratio of grain to straw rather than increasing the biomass itself. Increasing both the biomass and the yield of grain remains one of the great challenges of the future [see Appendix].

Chemical or organic fertilizers that provide plant nutrients are necessary to raise agricultural yields, as most soils do not have adequate nutrients to enable plants such as cereals to give high yields. Typically, most soils, whether under natural conditions or in agricultural use, release a meager 30 kilograms of plant nutrients per hectare per year, sufficient for a grain yield of only one ton to one and a half tons per hectare [Plucknett 1992]. As the high-yielding varieties responded well (and profitably) to the application of plant nutrients, there was an increased demand for fertilizer to boost yields. Between 1970 and 1990, when the high-yielding varieties were widely distributed, fertilizer consumption in developing countries rose by more than threefold (from 256 kilograms of fertilizer per hectare of available land to 833 kilograms per hectare), but the increases were more dramatic in the countries where the high-yielding varieties were most widely grown. In China, fertilizer consumption rose more than sixfold, from 460 kilograms per hectare to 2,619 kilograms per hectare. In India and Pakistan consumption rose by close to fivefold during this period, from 137 kilograms and 146 kilograms per hectare, respectively, to 687 kilograms per hectare and 890 kilograms per hectare. The largest consumer of fertilizer by this count is the Republic of Korea where consumption rose from 2,450 kilograms per hectare in 1970 to 4,250 kilograms in 1990. It should be no surprise that Korea now has the highest rice yields in the world, 7 tons per hectare. Nor should it be a surprise that the lowest consumers of fertilizers are the Sub-Saharan regions with their very low levels of corn and rice yields. Fertilizer consumption in Sub-Saharan Africa has risen from 33 kilograms per hectare in 1970 (used mostly on sugar) to 89 kilograms per hectare in 1990, slightly less than 10 percent of the average used in the developing countries as a whole [WRI 1992].

The "application of science" to agriculture included the use of chemical pesticides to control crop losses from anthropods, diseases and weeds. Synthetic pesticides were only discovered in the early 1940s but their use expanded rapidly, mostly in the developed countries. However, there is also a growing market for pesticides in the developing countries. Annual sales in South and East Asia are in the neighborhood of 2.5 billion dollars [World Bank 1992], and over 3 billion in Latin America [Dinham 1993]. Traditionally farmers in these areas limited losses from pests by relying on host plant resistance, natural enemies, cultural methods and hand weeding. However, the mass introduction of the new varieties and the spread of monoculture with dense stands of grain and continuous cropping in irrigated areas (especially rice) removed many natural constraints that held pests in check, and created a favorable environment for the rapid multiplication of pests. Soon relatively minor pests started to cause substantial losses [Pingali 1992]. The governments encouraged the use of pesticides (with subsidies and promotional campaigns) and farmers very rapidly expanded the use of the synthetic pesticides as they found them to be economic, reliable and labor saving. The financial returns on their use were very high.

There are no reliable or satisfactory analyses of the benefits and costs of using chemical pesticides. Losses from pests are said to be as high as 40 percent of the potential pre-harvest crop [Pimentel 1989]. There is no doubt that pesticides (such as DDT) along with chemical herbicides and fungicides have been effective in limiting crop damage (though it should be noted that, in the USA, the level of crop damage from pests has not fallen despite substantial increases in the use of pesticides). In the immediate post-war years pesticides also contributed substantially to reducing malaria, typhus and tripanomisias. The major costs arising from the use (and abuse) of pesticides include health-related costs. There is ample evidence of the health hazards to users of pesticides and to consumers of fresh fruits and vegetables that have been oversprayed [Hoppin 1992]. Excessive pesticide use has also damaged the environment by contaminating water and the atmosphere and poisoning the soil. In addition, excessive use of pesticides has reduced biodiversity and has helped kill the natural enemies of some pests, such as the brown plant hopper, so creating major problems for rice growers. Increasing use of pesticides has also contributed to the alarming growth of pesticide-resistant populations leading to a "treadmill effect" whereby ever more potent pesticides have to be introduced to deal with successive generations of pests [Hoppin 1992].

Given the imperative to increase yields, there will be a continuing struggle to reduce losses from pests without damaging human health and the environment. As a result there is a growing interest in integrated pest management which calls for carefully timed, selective spraying of pesticides, backed by the encouragement of natural predators and greater use of resistance varieties in crop protection. Chemical pesticides will still be used, but less frequently and in smaller amounts. Integrated pest management has been shown to be effective in Indonesia in dealing with the brown plant hopper with a far smaller input of chemical pesticides than in earlier periods. Hopefully, too, the manufacturers of pesticides will develop less toxic, less persistent and more specific chemicals. In addition, as is discussed in the Appendix, it is possible that the use of biotechnology will make a significant contribution to improving pest control without damaging the environment.

The expansion of irrigation was an essential component in the widespread adoption of the new varieties. The expansion of irrigation in dry areas removed the constraints to expansion imposed by lack of moisture. An assured water supply encouraged farmers to take the risks of purchasing the inputs needed to raise yields. The promise of the new technology with its higher yields induced governments and external financing agencies to invest in irrigation: returns on investment in irrigation were substantially higher compared with returns that would have been attained with the lower-yielding, traditional varieties. Irrigation expanded very rapidly in the period from 1960 to 1990 rising from 100 million hectares to 170 million hectares; and much of this area was planted to high-yielding varieties [see Chapter IV].

High-yielding varieties and other inputs have been adopted by increasing numbers of farmers throughout many different parts of the tropics. Starting from a low base in the 1960s, the use of improved seeds spread widely. By 1991, around 80 percent of the national wheat and rice areas and 50 percent of the corn areas in the major producing countries were planted with improved seeds [CIMMYT and IRRI 1987; 1988; 1989]. It is also estimated that as much as 90 percent of the irrigated and well-watered areas have been planted with improved varieties of wheat and rice [author's estimates]. There is still some room for the extension of the area planted to high-yielding varieties of different cereals. In many of these areas, though, the traditional varieties are better suited to the environment; and weather-related uncertainties make it risky for farmers to purchase those inputs needed to get high yields. Over time, many farmers in all environments have continued to replace the initial improved varieties with "upgraded" varieties.

The introduction and spread of the new varieties, along with the increase in the use of fertilizers, pesticides and the spread of irrigation, have contributed to the increases in average yields of the major cereals, especially wheat and rice. The high-yielding varieties of wheat were first introduced in Mexico when wheat yields were 750 kilograms per hectare. Following the introduction of improved varieties in the early 1950s, yields reached 1.37 tons per hectare and in the mid-1990s they reached over 4.4 tons per hectare. According to Dr. Norman Borlaug, the better farmers in Mexico now harvest 6.5 to 7 tons of wheat per hectare compared to 2 tons per hectare in 1945 [Borlaug 1987]. Similarly, average yields of wheat in India and Pakistan rose from less than 1 ton per hectare in the 1960s when the new varieties were introduced, to more than 2 tons in the late 1980s.

Average yields of rice and corn have also increased. Rice yields in the Philippines, where the first improved varieties of rice were introduced, rose from 1.53 tons of rough rice in 1966/68, to 3.11 tons per hectare in 1987/89 in the wet season, and from 1.60 tons per hectare to 3.20 tons per hectare in the dry season. Yield increases in other major rice producing areas also rose substantially.

The rate of increase in average yields in the countries as a whole has been impressive. Yields of wheat rose by 3.1 percent per year in 1960-1970, 3.5 percent a year in 1970-1980, and by 4.2 percent between 1980-1990. Rice yields rose by 2.7 percent, 1.7 percent and 2.5 percent over the same period. Yields of coarse grains rose by 3.5 percent, 2.5 percent and 1.5 percent over the years at a time when corn yields rose by 3 percent and 1.7 percent a year over each of the decades since 1970. Overall, the average annual increase in yields of cereals over the last 3 decades has been 2.6 percent a year (i.e., average cereal yield more than doubled over a 30-year period).

The increases in yields provided the basis for the rapid growth in output in most of the developing countries between 1960 and 1990. Where yield growth was slow, as in Sub-Saharan Africa, overall increase in output was also slow. One of the important questions for the future is whether the continued "application of science to agriculture" will provide a basis for sustaining the past high rates of growth in yields and whether this can be done without excessive environmental degradation.

Table 2.1. Increase in Agriculture and Food Production (1980-1991), Selected Regions.

1979-81=100	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
World agricultural production per capita	98.92 98.93	102.70 100.95	106.13 102.53	105.96 100.58	111.77 104.26	114.53 104.98	115.7 104.21	116.72 103.29	118.91 103.40	122.73 104.88	125.53 105.46	125.26 103.42
Developing countries' agricultural production per capita	99.10 99.14	103.99 101.88	107.89 103.50	111.94 105.14	116.61 107.22	120.60 108.58	122.43 107.92	125.08 107.96	131.58 111.21	135.05 111.77	139.53 113.08	142.79 113.32
World food production per capita	99.08 99.09	102.48 100.74	106.17 102.56	106.14 100.75	111.56 104.06	114,25 104.72	116.22 104.68	116.74 103.31	118.75 103.25	122.98 105.09	125.62 105.53	124.83 103.06
Developing countries' food production per capita	99.28 99.32	103.79 101.68	107.83 103.44	112.08 105.26	116.00 106.67	120.11 108.13	123.12 108.53	125.16 108.03	131.74 111.34	135.51 112.15	140.07 113.51	142.72 113.26
Asia food production per capita	99.09 99.13	103.95 102.08	108.35 104.43	114.59 108.38	119.37 110.78	122.19 111.29	125.83 112.48	127.55 111.90	133.94 115.34	138.39 116.98	144.35 119.78	146.99 119.73
Latin America food production per capita	99.43 99.45	103.57 101.33	107.46 102.85	107.55 100.72	110.61 101.39	115.74 103.86	114.91 100.97	119.31 102.66	124.29 104.77	126.60 104.56	127.53 103.25	128.57 102.06
Near East food production per capita	100.12 100.23	104.59 101.45	108.70 102.06	109.17 99.21	108.72 95.69	116.77 99.67	124.04 102.81	123.78 99.76	130.44 102.30	122.07 93.21	132.68 98.67	132.49 95.99
Far East food production per cap-ita	99.06 99.10	104.16 102.31	108.31 104.44	115.64 109.46	120.87 112.30	123.43 112.56	126.78 113.47	128.83 113.18	135.71 117.01	141.56 119.79	147.16 122.22	150.43 122.55
China food production per capita	98.76 98.76	102.50 101.26	111.03 108.39	119.30 115.08	128.07 122.03	128.59 120.94	134.17 124.47	138.83 126.96	139.89 126.06	144.31 128.11	157.15 137.44	159.39 137.34
India food production per capita	97.82 97.90	106.55 104.34	104.84 100.41	118.68 111.14	121.18 111.00	123.42 110.62	124.31 109.09	123.31 105.98	139.13 117.15	147.06 121.32	148.87 120.31	150.53 119.15

Source: FAO AGROSTAT Data Base 1992.

Table 2.2. Cereal Imports (growth by region between 1974 and 1990, in '000 metric tons).

	1974	1990	Difference	%
World	150,043	223,074	109,719	+73%
Developing Countries	68,820	113,355	44,535	+64%
Sub-Saharan Africa	4,209	7,838	3,629	+86%
East Asia and the Pacific	14,948	30,955	16,007	+106%
South Asia	9,404	5,724	-3,680	-39%
Middle East and North Africa	1,879	38,083	26,204	+220%
Latin America and the Caribbean	13,312	21,698	8,386	+62%

Source: FAO Trade Statistics.

Table 2.3. Contribution of Increases in Area and in Yields to Growth of Cereal Production, in Developing Regions and in High-Income Countries, 1961-1990.

Country Group	Increase Since 1961-1963 (percent)			Current Yield, 1989-90 (tons/ha)
	Total	Attributable to Area Increased	Attributable to Increased Yields	
Developing Countries	118	8	92	2.3
Sub-Saharan Africa	73	47	52	1.0
East Asia	189	6	94	3.7
South Asia	114	14	86	1.9
Latin America	111	30	71	2.1
Middle East and North Africa	68	23	77	1.4
Europe and former USSR	76	- 13	113	2.2
High Income Countries	67	2	98	4.0
World	100	8	92	2.6

Source: World Bank World Development Report

Table 2.4. Per Capita Water Availability from Domestic Supplies in 1990, 2025 and 2050, in Selected Regions and Countries.

Region or Country	Total Renewable Water Resources (cubic km)	Projected Population (thousands)			Per Capita Water Availability (cubic metres/person/year)		
	1990	1990	2025	2050	1990	2025	2050
AFRICA	4184.00	650,556	1,587,365	2,275,248	6,431	.2636	1,839
Ethiopia	110.00	48,784	123,302	178,949	2,255	892	615
Kenya	14.80	24,987	83,389	136,253	592	177	109
Lesotho	4.00	1,764	3,657	4,796	2,268	1,094	834
Nigeria	308.00	116,738	287,027	396,940	2,638	1,073	776
Somalia	11.50	6,285	14,840	25,751	1,830	775	447
South Africa	50.00	35,746	65,703	81,167	1,399	761	616
Tanzania	76.00	26,673	76,397	115,448	2849	995	658
Zimbabwe	23.00	9,925	19,923	24,969	2317	1,154	921
NORTH AFRICA							
Algeria	18.40	25,260	56,421	73,449	728	326	251
Egypt*	58.30	53,686	96,743	118,607	1,086	603	492
Libya	0.70	4,546	13,880	22,366	154	50	31
Morocco	29.70	25,128	46,994	58,151	1,182	632	511
Tunisia	4.35	8,140	13,669	15,965	534	318	272
SOUTH AMERICA							
Peru	40.00	21,627	36,377	42,667	1,850	1,100	937
ASIA	10485.00	3,099,790	4,901,246	5,728,310	3,382	2,139	1,830
China	2800.00	1,117,001	1,529,780	1,626,346	2,507	1,830	1,722
India	2085.00	847,728	1,361,318	1,602,339	2,460	1,532	1,301
Pakistan	298.00	114,290	285,264	398,147	2,607	1,045	748
MIDDLE EAST							
Cyprus	0.90	698	859	889	1,289	1,048	1,012
Iran	117.50	51,942	127,545	178,258	2,262	921	659
Iraq*	100.00	18,923	48,617	67,338	5,285	2,057	1,485
Israel	2.15	4,581	6,631	7,299	469	324	295
Jordan	1.10	3171	8,827	12,473	347	125	88
Kuwait	0.00	2,063	4,225	5,154	0	0	0
Lebanon	4.80	2,655	3,870	4,538	1,808	1,240	1,058
Oman	2.00	1,517	4,126	6,083	1,318	485	329
Qatar	0.02	389	785	962	51	25	21
Saudi Arabia	2.20	14,126	41,710	62,701	156	53	35
Syria	5.50	12,558	36,523	53,462	438	151	103
United Arab Emirates	0.30	1,592	2,613	2,947	188	115	102
Yemen	2.50	9,103	30,025	52,660	275	83	47

Sources: Computed from World Bank population data and projections; water availablility data from The World Resources Institute, 1992.
Note: Total Renewable Water Resources include all internally renewable flow, and flow from other nations.
* Without flow from other nations, Egypt would have water resources of only 1.80 cubic km, and Iraq only 34.00 cubic km.

1,000 cubic meters/person/year = "stress."

Table 2.5. Potential Crop Land in the Less-Developed Countries (million ha).

	Africa	South West Asia	South East Asia	Central Asia	South America	Central America	Total
Potentially Cultivable	789	48	297	127	819	75	2155
Presently Cultivated	168	69	274	113	124	36	784
Uncultivated:	621	0	23	14	695	39	1392
% of the region	79	0	8	11	85	52	65
% of all regions	44.6	0	1.7	1.0	49.9	2.8	100

Source: World Bank (1992) based on Buringh and Dudal (1987).

Figure 2.1. Production Indices Per Capita : Agriculture.

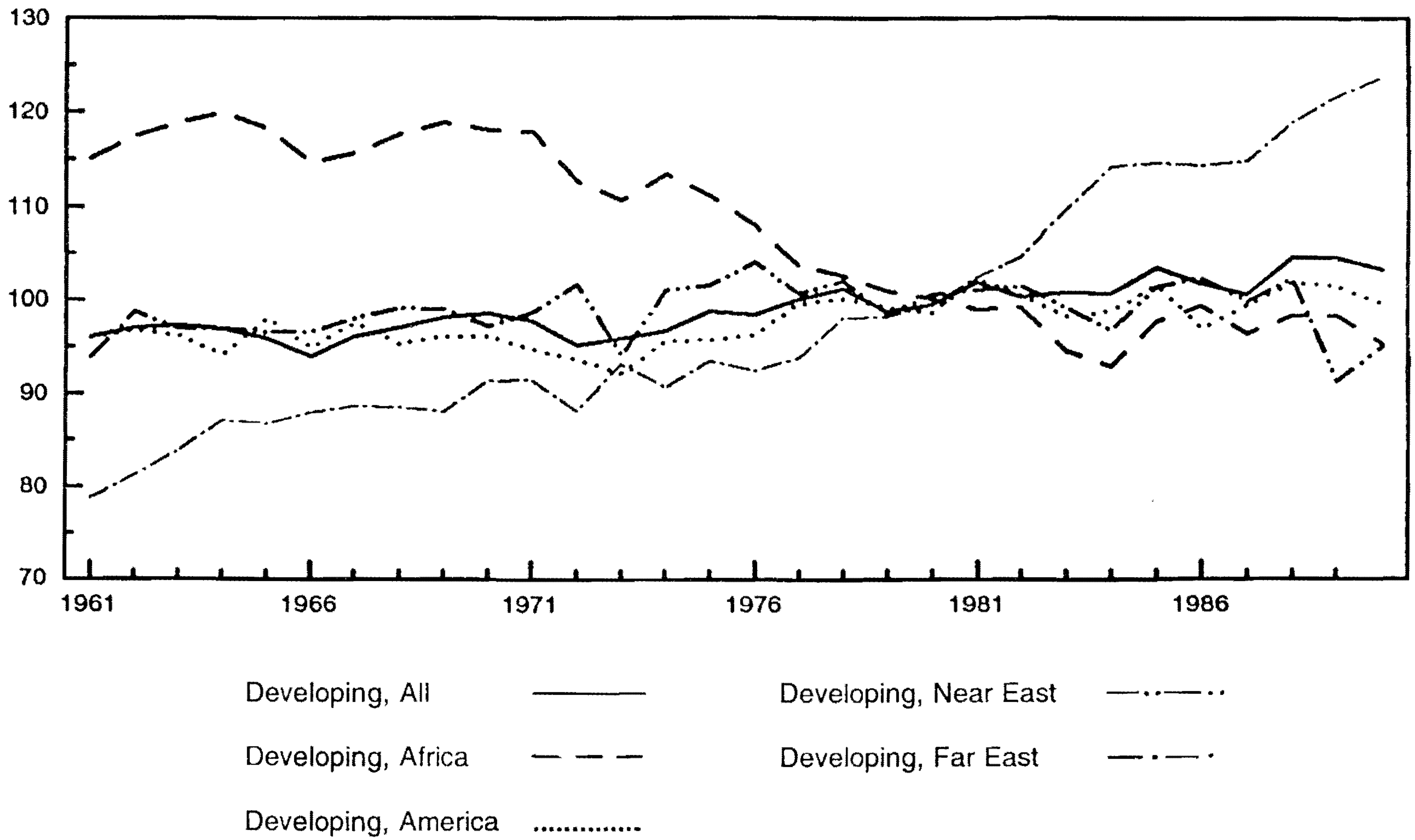
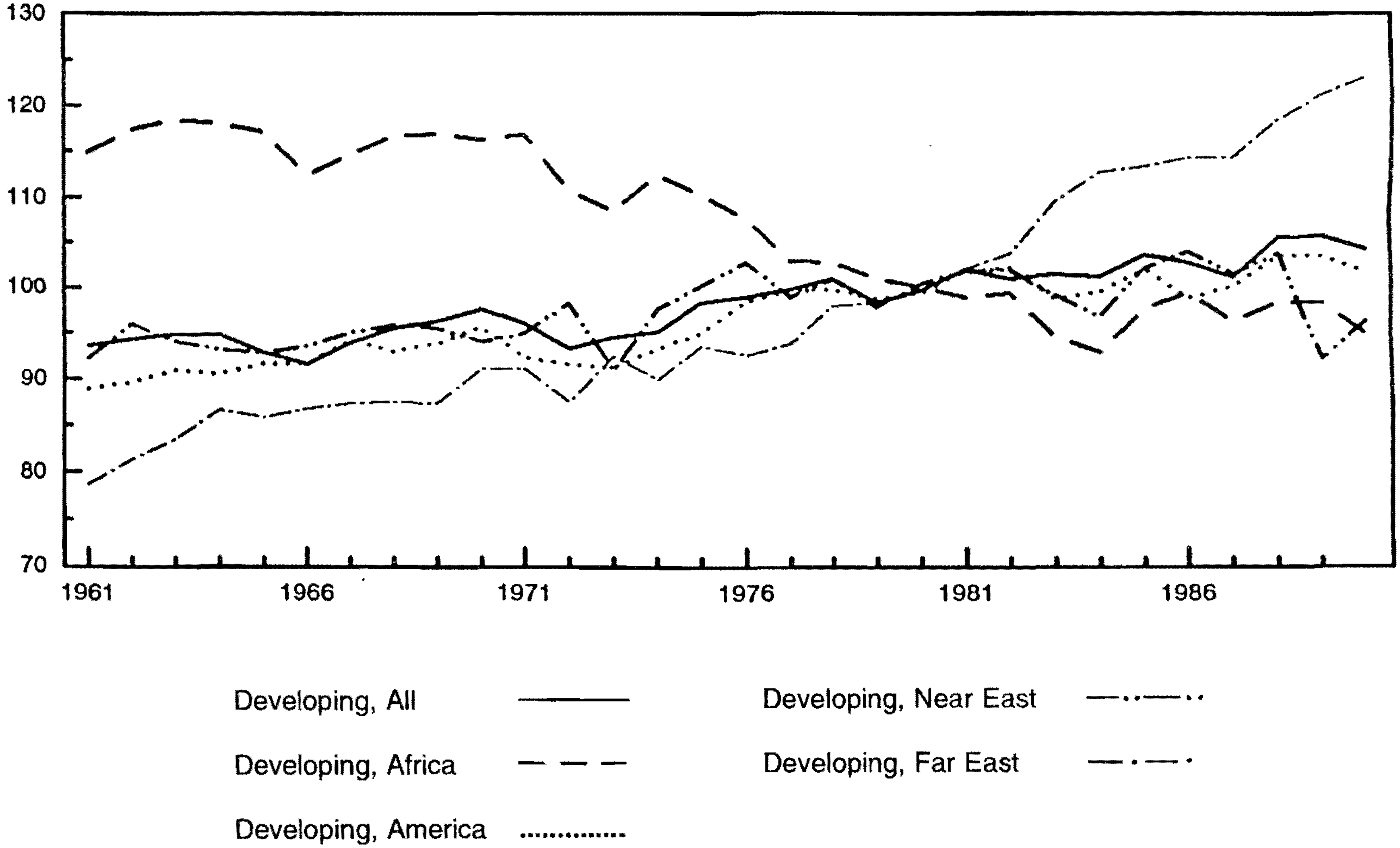


Figure 2.2 Production Indices per Capita: Food.



CHAPTER III

Future Supply and Demand

3.1 INTRODUCTION

This chapter estimates what kind of yield levels might be needed to satisfy the demand for cereals presented in the first part of this paper. Thereafter there is a consideration of past strategies for raising yields and some examination of whether past gains in yield increases can be sustained. Finally a judgement is made about the problems facing different regions in the future.

3.2 INCREASES IN YIELDS TO MEET DEMAND

There can be no doubt that the physical potential exists to increase food production substantially. A number of studies have concluded that the resource base of the developing countries, including the solar energy to raise the photosynthetic efficiency of crops, is adequate to provide food for more than 9 billion people. A basic assumption in many of these studies is that yields in developing countries will reach the levels currently enjoyed in the USA [Hudson 1989]. A more conservative analysis made by the Technical Advisory Committee [TAC] of the Consultative Group on International Agricultural Research [CGIAR] concluded that current levels of agricultural production could be more than doubled *without extending the area under cultivation.* An underlying assumption in this analysis is that current techniques will be used in an optimal manner "in an environment that is free of insects, pests, diseases and weeds and other optimal nutrient conditions" [TAC 1992].

All studies about the potential for expanding production assume that there will be a substantial increase in yields in the future; it is also assumed that it will be possible to match or emulate the record of the past thirty years when yields of cereals grew by 2.6 percent a year. This growth took place over a thirty-year period, 1960-1990, at a time when cereal production rose by 118 percent with 92 percent of that increase being attributable to increase in yields.

If estimated future demand is to be satisfied without any substantial changes in imports, especially rice, then production of cereals in the developing countries would have to rise by an average of 2.5 percent a year or by 150 percent over the 35 year period 1990-2025. If past trends continue, some 95 percent of increased output would have to come from higher yields. Average yields would have to rise from about 2.4 tons per hectare to 4.9 tons per hectare. This is about 0.5 tons above current averages in Europe [see Table 3.1].

The demand for rice is expected to grow by 2 percent a year up to 2035 and so will double by 2025. Close to 95 percent of the world's supply of rice is grown in land-scarce Asia. The area planted to rice has remained steady since 1980 and will probably continue to do so in the years ahead. Average yields will have to double to meet projected demand, rising from around 3.5 tons per hectare to around 7 tons per hectare or a yield that is as high as that of Korea, the country with the highest yields in Asia, and higher than yields in Japan (5.8 tons per hectare in 1990). Demand for wheat is expected to rise by more than 2.5 percent a year on average or by 150 percent by 2025. In recent years, almost all of the increase in the supply of wheat has come from increased yields (area under wheat actually contracted in the 1980s largely because of a reduction in area harvested in China) [CIMMYT 1989]. If it is assumed that 90 percent of the increase in wheat supply must come from higher yields, then average wheat yields will have to rise from 2.4 tons per hectare to 5.01 tons per hectare, or slightly above the current average yield in Europe.

The demand for coarse grains in general, and corn in particular, is expected to rise by 170 percent and 200 percent by 2025. The share of past increases in output of corn and coarse grains attributable to increased yields has fluctuated, as corn has displaced other coarse grains in several areas of the world. In the 1970s, 60-75 percent of the increased output of corn came from increased yields. Since a high proportion of corn and coarse grains is grown in land-extensive economies, where there are still prospects for expanding the area under cultivation, it seems reasonable to assume that around 70 percent of the projected increase in output will have to come from increased yields. Average yields of coarse grain and corn then would have to rise from 1.7 tons per hectare and 2.5 tons per hectare to 4 tons and more than 5 tons per hectare respectively. These yield levels are slightly below current average yields in Europe and North America [Table 3.1].

Looking further ahead, average yields will have to rise by something like an additional 70 percent to meet demand up to 2050. The *average* yields for all cereals would then be in the neighborhood of 7 to 8 tons per hectare; wheat and corn yields will have to rise to 9 tons per hectare and rice to around 12 to 13 tons per hectare. Clearly there will have to be great technological changes to meet these goals as these averages are close to or above the very best levels obtainable from existing technologies.

The projected increases in average yields are intended to give some indication of the order of magnitude of the growth in *average* yields required to meet projected demand by 2025 (always assuming that there is no substantial change in international trade in cereals). Average yields of course include yields from favored and less-favored environments. Unless there are some totally unforeseen technological changes, and a substantial expansion in irrigated land, the bulk of the increases in yield per hectare will have to come from lands where the availability and distribution of moisture is not a constraint on increasing output. At present this consists of 42 percent of the land under rice, 65 percent of the land under corn and 76 percent of the land under wheat. To raise average levels, the yields on these areas would have to surpass the current levels of yields in the developed countries and would have to approach or even exceed the current yield ceilings obtainable from existing technologies.

In the best of circumstances, raising average yields to levels comparable with the levels in the developed countries of Europe and in Japan will be a formidable task. The agroclimatic conditions in the temperate zones are much less harsh than in the tropics. In addition, the industrialized countries have a well-developed infrastructure and highly developed public and private service sectors to support agricultural development. Given the past rapid increases in average yields in much of the world, it would seem feasible to reach the levels needed by 2025, provided something like past rates of increase in yields can be sustained. But whether the favourable environment that encouraged technological change in the recent past will be present in the first part of the next century is an open question. This applies to economic considerations such as the level of prices for cereals and the availability of large supplies of aid as well as the potential for expanding irrigation, the development of new higher-yielding varieties of food crops and the opportunities for rapid growth from the initial applications of fertilizer on high-yielding varieties of cereals.

3.3. PAST AND FUTURE STRATEGIES

The strategy for increasing yields of the major cereals has rested heavily on improving plant varieties, increasing the use of agrochemicals and expanding the area under irrigation. The components of this strategy will continue to be central to raising yields in the future. However, there is growing concern, that it will be increasingly difficult to attain the needed yield increases without much more emphasis on improving resource management. There are three major reasons for this.

3.3.1 Future Varietal Improvements

One of the important issues is whether varietal improvements will continue to boost yields in the future. This question involves both the discovery of improved varieties of plants and their diffusion. The two most significant discoveries that provided the basis for yield increases in the recent past have been the introduction of hybrid maize and the modern high-yielding varieties of rice and wheat. These discoveries constituted important breakthroughs by providing the genetic potential for a quantum jump in yields (in the case of rice and wheat there was a 40 percent average increase in yield gain under moderate levels of fertilizer use). Since these breakthroughs there have been a number of varietal improvements (33 in rice alone) that have improved yield stability especially through major achievements in breeding for resistance to pests. But there has been little increase in potential for raising yields. In the case of rice there has been no increase in genetic potential since 1964; in the case of wheat there have been modest increases in genetic potential of between 0.5 percent and 1 percent a year; the genetic potential of corn has also increased modestly, but basically there has been a one-time jump in potential from hybridization.

There are prospects for increasing the potential for rice; IRRI is optimistic about developing new varieties that will give higher yields in different environments. It proposes to incorporate hybrid vigor that will help raise yields somewhat (hybrid rice is widely grown in parts of China). In addition, IRRI is hopeful about developing a rice variety that will raise the grain to straw ratio from 60:40, as at present, to 70:30. It is believed that this can be done by 2010 and that the new varieties of rice will be able to give a 25 percent increase in yields [IRRI 1991]. The outlook for wheat and corn is more problematic. There is every expectation that there will be continued average annual varietal increases of between 0.5 percent and 1 percent a year for wheat and small increases for corn. There is little optimism about achieving any major varietal breakthroughs similar to those in the early 1960s [Borlaug 1993].

The importance of discovering and distributing improved varieties with greater genetic potential is made evident by the fact that many of the better farmers in irrigated areas have already exploited the available genetic potential of the modern varieties. Many of these farmers, in parts of China, India, Mexico and the Philippines, are already bumping against the ceilings attainable with existing varieties [Borlaug 1993; Pingali 1991]. Thus the contribution to growth from varietal improvements is slowing down in the most favorable environments. It will also be increasingly difficult to raise average yields by expanding the substitution of high-yielding varieties for traditional and low-yielding varieties. This is because something like 80 percent of the rice and wheat areas, 90 percent of the area under irrigation, and 50 percent of the corn area are already planted to high-yielding varieties. There are still prospects for further growth through substituting hybrid corn for open pollinated varieties in areas where rainfall is adequate. There are also some prospects for replacing traditional varieties of wheat and rice with modern varieties, but by and large these prospects are limited compared with earlier periods. The future prospects for growth from improved varieties will depend very much on the success of researchers working in national and international agricultural research stations. Can they repeat the great breakthroughs of the 1950s and 1960s?

3.3.2 Future Impact of Agrochemical Use

A second issue of significance is whether there will be the same rapid increase in yields from the use of agrochemicals as in the past. There has been a very rapid increase in the use of agrochemicals, especially fertilizers, and to a lesser extent pesticides. The most rapid increases have been in Asia, though the level of fertilizer use per cultivated hectare is still only one quarter of the level in Japan. In the period 1960-90, incremental returns from using fertilizer along with high-yielding varieties of cereals were high because, inter alia, inputs started from such a low base. The evidence is sparse but it seems that the increased spread of more intensive use of fertilizers on some crops has led to diminishing marginal returns from adding fertilizer inputs. According to CIMMYT, "information from some parts of the world — Mexico, the Indian Punjab and Pakistan — indicates that the marginal returns to additional fertilizer use are now quite low" [CIMMYT 1989]. The same general conclusion seems to apply to some of the rice producing areas. It appears that over the longer run, yields of rice are stagnating in areas where there has been intensive cropping of rice including the use of considerable amounts of fertilizer. Increased inputs of fertilizer and micronutrients may well be necessary simply to maintain the existing levels of yields [Pingali 1991]. It does appear that there are diminishing returns from the use of agrochemicals in some of the most intensely farmed areas in the tropics. This will slow down the rate of increase in yields unless there is a higher level of resource management at the farm level.

There will also have to be a very substantial increase in the use of fertilizer to raise average yields. The obstacles to expanding fertilizer use in parts of the world such as much of Sub-Saharan Africa are formidable. There are very few effective distribution networks and there are major problems in delivering fertilizers to millions of small farmers in areas where infrastructure is lacking and transport costs are high [Yudelman 1987]. Elsewhere in parts of Asia, a combination of diminishing returns to fertilizer use, and rising marginal costs, at a time when the prices of commodities are either stable or falling, has led to a slowing down in the use of fertilizers [Rosegrant 1992].

There is no way short of some unforeseen technological breakthroughs (such as the development of techniques of nitrogen fixation) whereby raising average yields in the future can be achieved without a substantial increase in the use of agrochemicals. However, the slowing down of returns on fertilizers indicates that farmers will have to use fertilizers much more effectively in the future than was necessary in the past. This will involve a shift in approach from relying on added inputs to raise yields to one that gives greater emphasis on using these inputs more efficiently to raise productivity. Will this happen?

3.3.3 Future Expansion of Irrigated Area

A third question that will have a major bearing on future increases in yields is whether there will continue to be an expansion of irrigated area. More than 40 percent of the value of all grain produced in developing countries is grown on irrigated land, including 57 percent of the rice and wheat produced in these areas. The expansion of irrigation has contributed substantially to the rise in average yields of both rice and wheat. Generally, yields on irrigated areas are much higher than on non-irrigated areas. This is especially so in the 70 million hectares in the arid and semi-arid areas of the developing countries as well as in those areas that have a Mediterranean climate.

Between 1960 and 1990, the area under irrigation grew from 100 million hectares to 170 million hectares. The rate of increase in irrigated area, though, has fluctuated. Between 1960 and 1970, the area under irrigation increased by an average of close to 2.0 million hectares per year; between 1970 and 80 the average increase was 2.5 million hectares a year; but between 1980 and 90 the increase had fallen to 1.9 million hectares a year.

All indications are that the expansion of irrigation is continuing but at a declining rate, falling from more than 3 percent a year in the period 1970 to 1979 to an increase of 1 percent a year from 1980 to 1990. It appears that there has been a deceleration in investment in irrigation; much of the investment that is being made by the major financial agencies is in rehabilitation and maintenance rather than in expanding the acreage under irrigation [see Chapter IV].

If future rates of increases in yields are to grow as they have in the past, then it is difficult to perceive how this can be done without greater control over available supplies of moisture, the major factor limiting yield increases in many parts of the world. If past trends are to continue, then an average growth of 1.5 percent a year would mean an increase of close to 130 million hectares in irrigated acreage by 2025 and an additional 200 million hectares by 2050. *However, an increase of 130 million hectares by 2025 is greater than the UNDP and World Bank estimate of available non-irrigated area suitable for irrigation.* If past trends were to continue in Asia, the potentially irrigable land would be exhausted between 2015 and 2025.

In addition, if irrigation were to expand by 100 million hectares, this would run up against both physical and financial limits: 100 million hectares would require an investment of anywhere from

$400 billion to $800 billion at today's prices. It is highly likely that the rate of expansion of irrigation will be lower than in the past 30 years; it might well be between 1 and 2 million hectares a year, resulting in an additional 25 to 50 million hectares by 2025. After 2025, most of the expansion in irrigation would be in Africa and South America. A strategy of expanding irrigation to increase yields will continue to be important but there will be fewer opportunities for growth from this source than in the past; clearly much more emphasis will have to be given to making more effective use of *all* irrigated land than has been the case. Can this be done?

3.3.4 Improving Resource Management

The combination of a smaller varietal effect, diminishing returns to fertilizer use and the slowing down of the expansion of irrigation all make it problematic as to whether yield increases can rise as rapidly in the future as they have in the past. It appears that the "easy options" of the yield-increasing strategy have been exploited and future increases in productivity will have to be obtained by adopting a strategy that is somewhat different than the one followed in the past. For example, CIMMYT points out that it is possible that some further gains can be made by speeding up the diffusion of new wheat varieties and, in some cases, by increasing fertilizer use in irrigated areas. However, in its view, the emphasis should be placed on increasing the efficiency with which these inputs are used. Increased efficiency of input use may involve a range of other factors such as weed control, more appropriate crop rotations, reduction in harvest loss, promotion of integrated pest management, better timing of watering, and so forth [CIMMYT 1989].

In CIMMYT's view, "improved crop management will have to play a greater role relative to improved varieties in raising productivity." CIMMYT goes on to add that, "unfortunately many major wheat producing countries still lack the effective crop management research systems, strong extension systems and well-developed input support systems needed to effect this new strategy" [CIMMYT 1989]. The same general sentiment appears to apply to increasing yields of both rice and corn. While raising varietal potential may be essential for future yield increases, it appears that future gains will depend more and more on improving resource management (including water management). For rice this would include taking steps to offset the long-term stagnation of yields that is appearing in some areas by adopting "knowledge intensive techniques," including better soil and water management [Pingali 1991].

The importance of improving resource use extends to the environmental consequences of intensifying agriculture. Providing food for the world in the future will require extension of irrigation (probably including large-scale dams) and a much greater use of agrochemicals than in the past. This will place a premium on balancing increased production and safeguarding the environment. Thus in the future, more emphasis will have to be given to improving drainage to limit salination, developing integrated pest management approaches to limit use of toxic pesticides, avoiding contaminating land and water from excessive use of nitrates, and so forth. This will make the task ahead more difficult rather then less difficult.

One of the recognized achievements in the past has been that rising productivity, especially in Asia, has led to increases in low-cost supplies of cereals. This has helped keep down the prices of staples in both rural and urban areas. If food production does not increase at the same rate as in the past, it is possible that prices will rise. Rising prices should elicit increases in output, but the main burden of increases in prices will be borne by the millions of poor, urban consumers who have been the beneficiaries of past increases in agricultural productivity. Rising prices will help little if it merely leads to adding inputs as this would probably raise marginal costs substantially. An essential part of raising productivity will be through improved efficiency of resource use. This will be more difficult than spreading new varieties and fertilizers as it will involve the daunting task of educating hundreds of millions of farmers. Not an easy task.

3.4 CONCLUSION

The demand for food will increase at a lower rate than in the past in most of the developing countries as population growth rates have declined. The exception to this is in the Middle East and Sub-Saharan Africa where growth in demand will remain high before slowing down after 2010. Increase in demand for cereals will depend on whether the citizens of the developing countries follow the same patterns of consumption as in the industrialized societies. If they do, there will be an acceleration in derived demand for grains used for animal feed. Demand for wheat will continue to rise, but at a slower rate than in the past, while demand for rice will probably level off at a rate of around 2 percent a year up to 2025.

The supply of food and grain has increased at a very rapid rate over the period 1960-1990. The exception again is the Middle East and Sub-Saharan Africa. Growth in Asia has been impressive. Most of the growth has come from increased yields. In the future, yields will have to continue to rise because of limitations to expansion of acreage imposed by shortages of well-watered land.

It may be increasingly difficult to match past growth rates without a more efficient use of resources because of the special circumstances that prevailed in the earlier period: breakthroughs in varietal improvements in the major cereals, high returns from using agrochemicals because of a low starting base, and a very rapid expansion of irrigation. In this context it should be noted that the recent rates of expansion of irrigation appear to be unsustainable beyond 2020 or thereabouts [see Chapter IV]. In future, yield increases will have to come from improved technologies and a much more efficient use of resources. A more efficient use of resources will have to include the management of resources to limit environmental degradation from intensification of production. This will add to the burdens on those who have the responsibilities for persuading millions of farmers to undertake such tasks as to use water more efficiently, limit the use of pesticides, use the right mixes of fertilizers, weed more effectively as well as to maintain and manage water canals and the like.

There is a potential for expanding the area under cultivation in Latin America and Sub-Saharan Africa; but much of the potentially cultivable land is in remote areas and the quality of the resource base questionable (there are, however, prospects for opening up vast areas of Brazil to wheat production through the development of varieties that can give high yields in the aluminum toxic soils that have inhibited production up to the present). In some areas, notably the Middle East and North Africa, shortages of water are limiting the prospects for expanding food production. Over the longer run, water shortages may also be a constraint to agricultural development in countries such as Pakistan that rely heavily on irrigation, as well as in many countries in Sub-Saharan Africa.

The estimates of projected yield increases to meet demand are based on the assumption that countries would have a constant level of imports and that domestic supplies of cereals would provide the shortfall in demand beyond a fixed supply of imports. Once this condition is relaxed then increased imports *could* fill any shortfall in domestic production. This could well be the case in all cereals with the possible exception of rice, as most of the rice in the world is produced and consumed in Asia; very little rice enters international trade. In this regard, overall global supplies of food, especially wheat, may well increase substantially as the former Soviet Union "gets its act together." The former USSR was a large importer of grain and a wasteful consumer — average per capita consumption being by far the highest in the world. The region has the potential to increase production substantially and to become a major exporter by rationalizing domestic use of grain while increasing output. In addition, both the USA and the EC have demonstrated very amply that they can increase production substantially, provided they have the economic incentive to do so.

Taking both supply and demand into account it is possible to visualize a regional scenario up to 2025 as follows:

a. There will be severe constraints on food production in the Middle East and North Africa because of water shortages. Major challenge will be to manage available supplies to meet both urban and agricultural demands. The focus will shift to high unit value export agriculture and to importing of grains.

b. Sub-Saharan Africa will be hard pressed to satisfy growing demand for food from domestic production. The natural and institutional obstacles make it difficult for growth to rise from 2 percent to 3 percent to meet demand by 2025. Imports of grains, especially wheat, will probably continue to rise rapidly; even so, cereal imports into Africa will represent a small part of the global trade in cereals.

c. The major issue confronting Asian food production is that of intensifying production and raising yields in a region where irrigation has been the "engine of growth" and where there are increasingly limited prospects for expanding irrigation. Doubling yields of rice on existing areas will require a massive effort and might not be technically feasible. However, in the case of Asia, it may well be that a country such as China becomes an exporter of industrial goods and an importer of food. It is this uncertainty about China's policy that has led to such a wide divergence of estimates of future cereal imports into Asia. In any event it is probable that the global food situation will be dominated by events in Asia and the ability of Asians to raise their yields of cereals.

d. Latin America appears to be the region that has the most favorable resource endowment to increase output substantially in the future. It is feasible that Latin America along with the OECD countries and possibly parts of the former Soviet Union will become major exporters of grain to tropical Africa and Asia.

Looking beyond 2025, it is difficult to see the increases in yields and output, *based on existing technologies*, that will sustain the increased population in Africa and Asia. Both land and water will be constrained in Asia and water shortages will be an increasing problem in North Africa and parts of Sub-Saharan Africa and Asia. It is possible, though, to see a combination of technological improvements and changes in patterns of consumption that could meet demand by the middle of the next century. The technological changes could involve breakthroughs in biotechnology to increase the biomass of plants and their grain-to-straw ratios, increased drought resistance and nitrogen-fixing ability, and more direct conversion of the sun's rays into plant material. Other contributions could include large-scale, low-cost interbasin transfers of water, much greater sharing of international waters, as well as more fanciful changes such as nuclear fusion to desalinate sea water at low-cost, the low cost manufacture of nitrogenous fertilizers and other inputs. At the same time, a change in consumption habits could reduce resources being used for animal feed and free up resources for production for direct human consumption. Failing changes of these kinds, the temperate zones with their relatively small populations will have to be the granaries of the world.

Table 3.1. Yield Increases to Meet Demand for Cereals by 2025.

Commodity	Average Yield, 1991/92 (tons/ha)	Increase in Demand	Increase from Higher Yield	Yields, 2025 (tons/ha)	Average Yield in Developed Countries, 1991
Cereals	2.4	120%	95%	4.9	4.4[1]
Wheat	2.4	150%	90%	5.1	4.8[1]
Rice	3.5	100%	100%	7.0	5.8[2]
Coarse Grains	1.7	170%	70%	4.0	5.4[3]
Corn	2.5	200%	70%	5.2	5.4[1]

[1] Europe
[2] Japan
[3] North America

Sources: FAO Yearbook on production and authors estimates.

CHAPTER IV

Irrigation

4.1 INTRODUCTION

This section gives a brief background to the importance of irrigation in food production and points to a number of issues that warrant attention if irrigation is to be more effective in the future. The section starts with a description of the scope and diversity of irrigation and emphasizes the rapid spread of small-scale mechanical pumps, and their impact on water use, especially in Asia. Thereafter, there is a discussion of the importance of irrigation in food production and the rapid expansion of irrigation, and the recent slowdown in investment in expanding irrigation. The next part uses the results of an evaluation of a number of World-Bank-financed projects to provide insights into problems and difficulties of developing sustainable irrigation projects. The final section looks at the potential for expanding irrigation in the future and the apparent non-sustainability of expanding at recent rates of increase in irrigated acreage.

4.2 DIVERSITY AND TECHNOLOGY

Irrigation, defined as the "use of an artificial means to influence the supply of moisture to increase crop production," is practiced over much of the globe with varying degrees of sophistication. Technically, irrigation helps to raise and stabilize crop yields per hectare by reducing plant stress during periods of water shortage. Irrigation is practiced in a wide range of climates.

In 1990, 170 million hectares, or nearly 20 percent of the arable land in the developing countries, was irrigated; more than 85 percent of this was in Asia. As far as can be estimated, less than half of the irrigation in the developing countries is in the humid tropics [see Table 4.1]. As a general rule, irrigation in these climatic zones supplies needed moisture when it is not readily available during the crop growing season. This supplementary water from irrigation makes it possible to attain high annual yields with double, and even in some instances, triple cropping per irrigated hectare. Somewhere between 50 percent and 55 percent of the irrigated area is at the other end of the climatic spectrum in the arid and semiarid tropics and in the cool subtropics with winter rainfall in the Mediterranean Region of the Middle East and North Africa. In these climates, it is too dry to have any intensive crop production without irrigation. While irrigated systems in the humid tropics differ from those in the semiarid tropics, both systems have at least one important common impact on agricultural development. By providing regular and timely supplies of water, irrigation reduces the risk of crop losses from uncertain rainfall. All other things being equal, this encourages farmers to invest in land improvements and to use "purchased inputs" to increase production. As has been pointed out, the expansion of irrigation has gone hand in hand with the the spread of modern varieties of seed, and the widespread use of fertilizers and pesticides. In addition, in many areas, the expansion of irrigation has provided a basis for the growth of investment in "off-farm"-related agro-industries, and distribution facilities.

Irrigation schemes can be diverse and vary greatly in size and scope. The range can be highlighted by contrasting the situation in the Indus Area of Pakistan with that in parts of West Africa. Pakistan possesses the world's largest contiguous surface distribution system, comprising the Indus River and its major tributaries, 3 large storage reservoirs, 19 barrages, 43 main canals, 12 link canals and about 89,000 watercourses. The total length of the canal system is about 58,300 km of conveyance facilities. Watercourses from channels and field ditches amount to more than 1.62 million km in length [Ahmad and Kutcher 1991]. In all, the canal-commanded areas cover close to 16 million hectares. This system provides water for millions of farmers who are linked together by being part of a distribution network that is largely controlled by a centralized management system.

In all of Sub-Saharan Africa, about 5 million hectares are irrigated — less than one third the area in Pakistan — and about half of the irrigators are described as being small-scale and traditional. In the semiarid Sahel Area, there are many small-scale schemes that rely largely on conserving moisture that comes from short, heavy seasonal rains. Irrigation is usually based on water harvesting, using earthen or stone bunds to trap water, to provide moisture to irrigate very limited perimeters, seldom more than one or two hectares in area. These irrigated perimeters are widely dispersed and are used for grain, vegetable and fruit production with very little in the way of purchased inputs. There is little organized control or management over a dispersed irrigation effort [Yudelman 1991].

There is also 'run-of-the-river' irrigation, which depends on river flow and is closely correlated with rainfall. Run-of-the-river schemes, such as those in Indonesia and Thailand, cover vast areas and make a limited, but very valuable contribution in the dry season, and a potentially larger, but not always needed one in the wet season when the rainfall is usually adequate for growing flooded rice. Water from these schemes is delivered to rice fields by gravity (frequently free of charge to farmers) along primary and secondary channels, and then tertiary channels at the farm level. The success or failure of these schemes depends on many factors, but not the least important is the timeliness of the rain.

A recent study of irrigation management on the Indo-Gangetic Plain captures the immense complexity of dealing with the problems of this area. The study states:

> The Indo-Gangetic plain contains perhaps 40% of India's population and 50% of its irrigated area. In the west (Punjab, Haryana) it covers one of India's most productive regions, in the east (Bihar, W. Bengal) one of its least productive. Between these extremes, there is a gradual transition in physical and socio-economic conditions, with rainfall, kharif cloud cover, surface flooding, rural population densities and subsistence farming generally increasing, and agricultural yields decreasing, from west to east. Understanding how these factors interact

explains much about the region's economic history, its irrigation issues, and possible approaches to it irrigation management problems.

Irrigated agriculture's relative success in the west and relative failure in the east can be very largely attributed to differences in rainfall. In the east, rainfed cropping is viable and the full farm is cultivated. In a drought, all crops require water irrespective of whether they are authorized for irrigation or not, while if it rains no water may be needed - indeed too much water can do harm. Great variation in need results in farmer interference and greatly complicates irrigation management. In contrast, if rainfed cropping is marginal, as in the west, farmers plan their activities in expectation of irrigation rather than rainfall. Since irrigation is much more predictable, demands are stable, farmer interference is minimized and management is greatly simplified.

It is inherently more difficult to improve management in the east than the west. The first step must be to gain control since otherwise no management is possible. To achieve control, trade-offs may be necessary between the detailed ability to respond and manageability. Since water is scarce relative to land, the objective must also be conjunctive use defined here as the *optimum use of surface water, groundwater and rainfall under conditions where the only significant practical public intervention is the way that water is distributed in time and space in the surface system.* Management is thus the key in large surface systems to the use not only of surface water but also of rainfall (the largest resource in quantitative terms) and groundwater (the most valuable resource given the control it allows the farmer). It may also be an important contributory factor to resolving drainage problems which in the east can be the dominant constraint and which in the west must be resolved if irrigated agriculture is to be sustained over large areas underlain by saline groundwater. [Berkoff 1990]

4.2.1 "The Pump" Revolution

Most of the major surface irrigation projects in the developing countries are large-scale public-sector projects funded by government or state revenues and managed by public-sector officials. However, recent technological changes have brought an important private-sector component into the picture. The development and diffusion of inexpensive, internal combustion engines and pumps have made it possible for individual farmers or groups of farmers to use small wells to exploit shallow groundwater aquifers, and to use low lift pumps for drawing water from rivers and channels to irrigate rice in the "dry season." Expansion has been most pronounced in Asia although pumps are being used increasingly, but still in a limited way, in parts of West Africa (largely for producing vegetables).

There has been a proliferation of wells owned by individuals in South Asia and by groups in China [Yudelman 1989]. Private groundwater development has enabled large areas with good land and irrigation potential to be brought under production quickly, almost certainly more rapidly than would have been the case in state-controlled projects. In Thailand, there are more than 5 million small pumps used primarily to lift water out of canals and rivers for use on rice paddies. The spread of private wells has been most notable in India: the number of wells increased from 459,000 units in 1968 to 3.3 million units in 1984/1985. Within India, in the state of Uttar Pradash, privately owned tube wells increased more than tenfold from 120,000 to 1.6 million during this period. About 1.1 million of the 1.6 million tube wells are diesel-powered with the remainder using electric pump units. About half of the irrigated area is now said to be served by underground water. Much of this is in command areas, and complements the use of surface water [Yudelman 1989].

The spread of power-driven pumps has contributed greatly to the increase in food production in countries such as India, but at the same time it has made agriculture more dependent on sources of off-farm energy than before. The farmers' choice among various types of power-operated private wells depends on many factors, including groundwater characteristics, size of their holdings, available finances and the availability of power. Initially in countries like India, most pumps were diesel-powered; rural electrification was limited. In the recent past though, the unavailability and cost of diesel fuel have caused problems. There have been severe fuel shortages, sometimes during the critical periods of the cropping cycle. At the same time, there has been an expansion of the rural electrification network. It is clear that the source of power used by farmers will be sensitive to the cost of energy, especially since, unlike surface irrigation, operating costs constitute so large a proportion of total costs of irrigation by tube wells.

The spread of privately owned wells has surged forward, and private groundwater development in places like central India and parts of Bangladesh appears to have been a great success. However, there appears to be a lag in the institutional, legal and technical development to manage this phenomenon in such a way as to safeguard the natural resource base, promote equity and optimize the use of water [Le Moigne et al. 1991]. This is partly due to a lack of adequate information to make sound judgments about the extent to which the groundwater table is being depleted. This deficiency can only be remedied by improving monitoring, and looking at the total impact of unregulated development of private wells on the water supply and the efficiency of water use. There needs to be an analysis of what this expansion means in terms of the utilization of physical resources (including groundwater) and energy, as well as the financial implications in terms of subsidizing the wells through low-cost electricity. It appears that subsidizing electrical power is leading to wasteful use of water [Malik and Faeth 1993].

In summary, it is clear that there are a large number of different irrigation schemes in Asia, Latin America and Africa. They take many forms and embody a wide range of systems, relying on impounded surface water, run-of-the-river approaches, or lifting water from aquifers. A significant development in irrigation technology, especially in Asia in recent years, has been the widespread growing use of small power-driven pumps to lift water from aquifers, canals and rivers for use on agricultural plots. The dispersion of these pumps has been important in improving water use and water efficiency, especially in areas where there has been seepage from canals. The spread of pumps has also been important in encouraging private initiative and opening the possibility of flexibility in the use and marketing of water for irrigation. However, as has been pointed out, there is need to ensure that "the pump revolution" is sustainable, and that it does not deplete the natural resource base. This will call for monitoring and possibly some control without unduly stifling initiative.

4.3 THE EXTENT OF IRRIGATION

The quality of data on area under irrigation leaves much to be desired. The compilation of national data on land and water use is usually the responsibility of one or another governmental agency. Invariably, these agencies are underfunded and lack the resources to monitor changes, or to undertake sample surveys to verify estimates derived in large part from reports from field offices. Data are often exaggerated for political reasons or to impress donors. Different countries use different definitions of irrigated lands, making aggregation difficult. Some definitions of irrigated area encompass land actually irrigated, while others consider land that could be irrigated, using existing facilities, to be defined as irrigated land. In addition, most definitions refer to irrigated land as area irrigated or potentially irrigable regardless of whether it is irrigated only once or several times during a year. There is little aggregate data on the intensity of land use or the crop areas irrigated. Experience has shown that different departments in the same government give different estimates of area irrigated: for example, the Department of Agriculture reports one set of estimates, while the Department of Irrigation reports another set.

According to FAO, there were close to 868 million hectares of arable land in use in the developing countries as a whole in 1989/90; 173 million hectares, or 19.9 percent of all arable land is reported to be irrigated. The distribution of irrigated area is heavily concentrated in Asia, with 131.7 million hectares, or 78.2 percent of all irrigated land in the developing countries. The Middle East and North Africa have 18.6 million hectares, or 10.7 percent of the irrigated area, Latin America and the Caribbean have 14.07 million hectares, or 8.1 percent of irrigated area; while Sub-Saharan Africa has 5 million hectares and only 3 percent of the irrigated land in the developing countries [see Table 4.2]. Three countries in Asia — China with 45 million hectares of irrigated land, India with 43 million hectares, and Pakistan with 16 million hectares — account for two-thirds of all irrigated land in the developing countries. The next three most important countries in terms of irrigated area are Indonesia (7.3 million hectares), Iran (5 million hectares), and Mexico (5.3 million hectares). The remaining countries have less than 5 million hectares of irrigated land each. No country in Sub-Saharan Africa has more than 1 million hectares under irrigation.

4.4 THE CONTRIBUTION OF IRRIGATED AGRICULTURE TO FOOD PRODUCTION

One measure of the importance of irrigation as a factor in agricultural development is the share of food and agricultural output that is produced off irrigated land. The Technical Advisory Committee (TAC) of the Consultative Group on International Agricultural Research (CGIAR), acknowledging very thorny problems of valuing both traded and nontraded commodities, has estimated that between 1987 and 1989, the annual value of all crop production in the developing countries was in the neighborhood of $364 billion dollars; it is estimated that $104 billion dollars worth of crops, or 28.5 percent of the value of all production, was produced on irrigated land. More than 30 percent of all food production, valued at around $96 billion, was grown under irrigation. Perhaps irrigation's largest contribution to both consumers and producers is that an estimated 46.5 percent of all grain and 57 percent of the total value of the most widely grown basic staples, rice and wheat, were produced under irrigation [see Table 4.3].

Irrigation's contribution to production is best measured by isolating the contribution of controlled supplies of water to output. The contribution of each input cannot be measured by simply considering the difference in output with and without each input because of the strong interaction among the inputs. The impact of the joint effect of the inputs on output can only be estimated under carefully controlled multifactor experiments. Such an experiment was undertaken by IRRI in the early 1970s. The experiment sought to explain the differences in yields of rice obtained at the farm level compared with the attainable potential as demonstrated on research stations. A conclusion was that the "lack of control over water is the single biggest constraint. If all rice was fully irrigated, maximum yields could average 5.6 tons per hectare . . . water control is responsible for 23 percent of the difference between maximum possible and actual yields" [Herdt and Wickham 1978].

In a more general sense, the importance of irrigated agriculture as a whole is also shown by the aggregate difference in productivity between irrigated and nonirrigated land. Overall, close to 20 percent of the land under production produced 28.5 percent of the value of crop production in 1987/1989, and 30 percent of the food production off a smaller area. Therefore, broadly speaking, the value of output per hectare was substantially higher on irrigated than on nonirrigated land, even though much of the output on irrigated land, especially in Asia, is low unit value grain. Average yields of grain on irrigated land are frequently twice as high as averages on nonirrigated land.

On a regional basis, it is estimated that around 60 percent of the value of crop production in Asia is grown on irrigated land. This includes around 80 percent of Pakistan's food, 70 percent of China's and more than 50 percent of India's and Indonesia's food. In the Middle East and North Africa, more than one-third of the region's crop production by value is irrigated, including all the food grown in Egypt and more than half of that grown in Iraq and Iran. A relatively small proportion of agricultural production in Latin America, around 10 percent, is grown under irrigation, but more than half of all the food crops grown for export in Chile and Peru are irrigated. Sub-Saharan Africa, with the smallest regional area under irrigation, produces an estimated 9 percent of its total food production on irrigated land. Madagascar produces more than 20 percent of its agricultural output and food from irrigated land.

The irrigated sector performs an essential task in meeting the basic food needs of billions of people in the developing countries, especially in Asia. In the past, it has provided more than half of the two most important basic staples and close to a third of all food crops. In the future, given the importance of increasing yields, the irrigated sector will have to provide an even larger proportion of total food output, especially in Asia.

4.5 THE EXPANSION OF IRRIGATION

There has been a rapid expansion of land under irrigation, especially in the 1960s and 1970s, though in recent years the rate of expansion has slowed down. Historically, the total area under irrigation is estimated to have been something like 8 million hectares by 1800. Between 1800 and 1900 it is reported to have grown to around 150 million hectares. Much of this expansion was under colonial regimes in South Asia and East Asia where engineers laid out canal systems that are still an important part of current systems in use in parts of South Asia and Java. During the twentieth century there was a further steady expansion of irrigation in the developing countries so that by 1960 it was estimated that slightly more than 100 million hectares were under irrigation.

Since the 1960s, there has been a continuing increase in the area irrigated. Between 1960 and 1990 irrigated area increased by 74 million hectares with the total under irrigation reaching 174 million hectares in 1990. The largest increases were in Asia where irrigated area, mostly in Pakistan, India and China, increased by 60 million hectares [see Table 4.4].

The rate of expansion of irrigated land has been uneven. Between 1960 and 1970 irrigation expanded by 22 million hectares; over the next 10 years, 1970-80, irrigation expanded more rapidly, rising by an additional 25 million hectares, but there was a decline in the rate of expansion in the next 10 years as the area under irrigation grew by 19 million hectares. Thus the average annual expansion was 2.2 million hectares between 1960 and 70, 2.5 million between 1970 and 1980, before falling to an average of 1.9 million hectares a year in 1980-90. Since then the average annual expansion appears to have declined further.

Recent trends in international aid for irrigation indicate that it is unlikely that there will continue to be the same high growth rate in area under irrigation as in the 1970s. Between 1976 and 1981, some $8.7 billion were committed by donors for expanding irrigation — this represented 20 percent of all aid for agricultural development over those years [Carruthers 1983]. The largest commitments were made by the multilateral agencies, notably the World Bank, which committed close to $4.4 billion for this purpose. Between 1950 and 1982 the World Bank loaned $10 billion for irrigated development with 90 percent of these loans being made in the 1970s. These loans averaged around 40 percent of the total cost of the projects, so Bank-supported irrigated projects involved total investments of $25 billion. Since the late 1970s, though, lending for irrigation has slowed down considerably. The World Bank's lending for irrigation, in real terms, has fallen sharply from a peak in the late 1970s to a low level in 1989 before a one time rise in 1990 [see Figure 4.1].

The same tendency is apparent in regard to loans for irrigation in Asia made by all the main external financing agencies, including the Asian Development Bank, the Japan Overseas Economic Development Fund, and the U.S. Agency for International Development. Lending and assistance for the region as a whole reached its peak in real terms in 1977-1979. By 1986-1987, it was less than 50 percent of the 1977-1979 level. (The decline was steep in Southeast Asia, falling from a peak of an annual average of $630 million in 1977-1979 to $202 million in 1986-1987.) By all accounts, the low level of lending for new irrigation projects, by all donors, not only the World Bank, has continued so that the prospects do not seem to be very favorable for a substantial increase in externally funded irrigated acreage in the short or medium term [Svendsen and Rosengrant 1993].

An important reason advanced for the slowing down of investment in expanding irrigation has been the unfavorable economic outlook for new irrigation projects, especially in the cereal producing areas. This applies with special reference to large-scale surface irrigation projects. There is a general view that most of the "best" sites with "low cost opportunities" for impounding water for redistribution have been exploited. The real cost per hectare of newly irrigated land is higher than the average cost of the 1950s, 1960s and 1970s. Between 1966 and 1988 real capital costs for construction of new irrigation systems in Asia are estimated to have risen by between 70 percent and 160 percent per hectare, with the largest increases being in Sri Lanka and the smallest in

Thailand [Rosengrant 1991]. At the same time, the expected value of output from many of the potentially large-scale irrigated projects has not increased, and in some instances has actually declined compared with earlier periods. This is most evident in the case of rice, the most widely grown of all crops under irrigation. The trend in international prices of rice has been downward over the past decade, and is projected to continue to remain at a low level for the foreseeable future. Wheat prices have also fallen steadily over the last several decades, and the outlook for future prices is clouded by the prospect of substantial increases in production from the former Soviet Union and Eastern Europe when these regions overcome their current economic difficulties.

The decline in investment in new projects is leading to a paradoxical situation. Over the longer run, more irrigated land will be required to meet the increasing demand for food; however, if investments are to be guided by the economic criteria used at present, then these investments may not be forthcoming. Given the long lead time — up to 15 years or more — between planning a large project and its full implementation, this could lead to a situation of shortage in the future. If investment decisions were to include special allowances for promoting food security, then due account could be taken of the link between growth in irrigation and the future supply and price of rice. Since the supply of rice is linked to the expansion of irrigation, the supply is endogenous to irrigation (i.e., the future price depends on current investments). In the light of this, there may well be merit in reexamining the prices used in appraising the economics of irrigation projects. The argument here is that rice prices will rise without added investment in irrigation, therefore this warrants the use of a marginally higher price for rice in considering the benefits for future investments in irrigation [Rosengrant 1991]. Alternatively, the discount rate for *all* investments can be lowered, making more investments in irrigation economically acceptable to major investors.

There are other reasons for the reduction in investment in irrigation. Some of these include doubts that have been raised about the success of past projects. These doubts include concerns about the environmental impact of dams and tubewells, and the degradation of natural resources as well as doubts about the financial viability of a number of the past investments. Many of these problems, as discussed below, have been highlighted in evaluations of the impact of projects that have been implemented; they provide the basis for some of the recommendations for future research outlined in Chapter V.

4.6 PROBLEMS IN IMPLEMENTING IRRIGATION PROJECTS

4.6.1 Introduction

There have been a number of evaluations, by bilateral and multilateral agencies and national governments, of the problems in implementing irrigation projects. Many of the issues raised by these evaluations have contributed to the reluctance to invest in expanding irrigation. Our present purpose is to highlight some of the major concerns that will require continuing attention if investments in irrigation are to be more successful than in the past.

The evaluation used here to highlight the major issues related to irrigation investments in the 1960s, 1970s and early 1980s was undertaken by the World Bank in 1990. This evaluation analyzed a range of Bank-supported irrigation projects from 5 to 12 years after the completion of the funding of these projects. The evaluation covered a fairly representative group of 21 irrigation projects in 14 countries initiated and implemented between 1970 and 1986. All were intended to increase food production, and involved a total investment of some $1.8 billion. The average cost per project was estimated to be $61 million at appraisal, but was actually $85 million upon completion (40% cost overrun). The projects included 14 gravity schemes, 4 pumping schemes, and 3 sprinkler irrigation schemes; eleven projects involved construction of new irrigation and drainage, 9 rehabilitated and extended existing schemes and one rehabilitated an existing system. The areas irrigated under the projects ranged from 1,200 hectares to 291,000 hectares with an average of about 50,000 hectares per project. The spread in actual cost per developed hectare was from $1,460 to $14,012 in 1988 dollars [World Bank 1991].

The general conclusion of this evaluation was that "though the projects were beneficial, they performed much less well than expected." Most of the projects made important contributions to national food supplies, raised the income of low-income farmers and, in all but one case, improved the average family income and standards of living of those working in the irrigation schemes (though by less than anticipated). The impact on income distribution among the beneficiaries of these projects was mixed, depending in large measure on the patterns of landholding in the areas served by the projects — where the pattern was skewed, the distribution of benefits tended to be skewed. The projects also contributed to the enhancement of the physical environment by reducing the extent of periodic flooding, and by propagating fish and wildlife in and around some of the reservoirs that were constructed.

Despite these positive results, the evaluation pointed to a number of problems in implementation of these projects which in many ways are a microcosm of the larger concerns about the effectiveness of investment in irrigation. These problems are outlined in the remainder of this section.

4.6.2 The Economic Rate of Return and Effective Use of Capital

The economic rate of return or the internal rate of return on an investment in a project is now widely used by international agencies, bilateral donors and many governments as the main "performance indicator" to determine whether a project can be expected to provide a satisfactory return to an economy (and also whether there is an alternative way of achieving the same objectives that would offer a higher return) [Baum & Tolbert 1985]. The calculation of the economic rate of return and the theory underlying its rationale have been the subject of arcane debate. In general terms, the calculation of the economic rate of return involves estimating future streams of costs and benefits that are expected to flow from an investment over the estimated life of the project; thereafter, the values of these streams are discounted back to the present. The discount rate that gives a zero net present value for the project is the internal or economic rate of return. In most agencies, including the World Bank, if the discount rate exceeds the opportunity cost of capital it is usually concluded that the project is justified.

The opportunity cost of capital is the return that can be made from alternative uses of that capital in national or international markets. However, the opportunity cost that is usually used is a notional concept that reflects a judgment on what these returns should be. The opportunity cost of capital could vary from country to country but, as a general rule, agencies like the World Bank use one rate for all countries. For some years now, this rate has been 10 percent in real terms (i.e., after inflation). Thus a return of 10 percent is the "cut off" point for investments in irrigation projects, as it is with all output-generating projects.

The *ex post* economic rate of return on the 21 projects under review ranged from minus 5 percent to 30 percent. The weighted average return was 9.3 percent. Eleven of the projects had a rate of return of above 10 percent; therefore, by the standard currently used in the Bank and other agencies, capital was used efficiently only in slightly more than half of the projects. However, if the opportunity cost of capital were placed at 8 percent (in real terms), which many would consider to be a reasonable rate of return on an international investment, then 75 percent of the projects would have been "successful." The same general principle applies to *ex ante* analysis — a lower discount rate than that currently being used could well lead to an increase in investments in irrigation. There is surprisingly little discussion over this issue or pressure to change the discount rate among the major international lending agencies.

The evaluation of the 21 projects makes it clear that nearly all of the irrigation projects gave lower economic rates of return than anticipated. This was not because of a decline in prices of output (although prices of output were lower than expected in 7 projects) but rather because of water shortages (11 projects), poor drainage (11 projects) and smaller than planned irrigated perimeters. There was *no* correlation between the economic rate of return and the nature of the project — whether the investment was in a new project or in rehabilitating existing works. In addition, there was no correlation between the efficiency of use of capital and the *size* of the investment, including the size of dams.

A general conclusion confirmed by other evaluations is that the more careful and thorough the project preparation, the greater the probability of projects giving higher economic rates of return. Better project preparation has been constrained by a lack of reliable information and data on many aspects of the resource base, especially the nature of the soils and availability of water in the project areas. The shortage and, often, the absence of basic data at the project level mirrors inadequate information about natural resources in general. However, if past experience is any guide, then a "two stage" approach can ease this problem. The first stage is used to gather data by rapid surveys while the subsequent stage is used for project preparation. Better preparation could well lead to a more efficient use of capital in investments in irrigation projects.

4.6.3 Operation and Maintenance

A serious issue in the implementation of the 21 projects was that the poor maintenance of these projects impeded the efficient use of available water and shortened the life of the investments. Maintenance was considered "satisfactory" in only four of the projects and unsatisfactory in 13 of the 17 projects that included civil works. The useful life of all works was expected to be 50 years in 7 projects, 40 years in 3 projects, and 30-35 years in 10 projects. However, less than 10 years after most of these projects were in operation, it was apparent that a high proportion of the works would not function effectively for their projected life spans. Many of the projects were already in need of rehabilitation. The main reasons advanced for the poor maintenance were poor construction standards, insufficient funding for recurrent expenditures, and lack of systematic plans for maintenance.

Many studies have documented reasons for the poor maintenance of irrigation projects. These include everything from failure to check upstream erosion, leading to siltation and sedimentation in reservoirs, to difficulties in organizing water users to keep canals free of weeds. Some of these studies touch on issues that extend beyond the purview of the usual official reviews. Well-documented studies have laid emphasis on corruption being an important factor in the poor operation of systems, and in the use of shoddy, substandard materials that depreciate very rapidly [Wade 1982 and 1985]. Other studies emphasize that a big drawback to maintenance is the shortage of funds, usually recurring expenditures, for paying salaries needed to maintain irrigation systems in working order. These studies emphasize that funds for this purpose are scarce, because inter alia, preference is given to new projects that earn political prestige, and because foreign donors prefer funding capital works to financing rehabilitation and maintenance that require a high proportion of recurrent expenditures [Yudelman 1989].

Most governments and donors have come to recognize that poor maintenance has been, and still is, an obstacle to improving water use efficiency in surface and tube well irrigation (especially in public-sector projects). Earlier notions of introducing "foolproof" high technology systems as a substitute for poor management have given way to a recognition that "low-technology" systems and improved management have to go hand in hand to improve the efficiency of water use. This will require increased resources for training and operating costs. Resources are being shifted away from investment in creating new capacity to improving existing capacity. One of the open questions, though, is whether investments in rehabilitation are simply "repairing" inefficient systems or whether they are also being used to modernize and improve poorly designed older systems such as those in India and Pakistan which are much the same as they were at the turn of the century.

4.6.4 The Efficiency of Water Use

The efficiency of water use was reported to be low in most of the projects reviewed in this evaluation. Part of the reason for this was poor maintenance that led to crumbling and leaking canals, ineffective sluice gates, and choked and untended watercourses. In addition, water control systems were beset by operating deficiencies.

There are also the more general institutional problems. One such problem, especially in large-scale surface systems, is that efficiency in water use requires close cooperation between the managers and operators of water systems and the water users so that water can be delivered when needed to fit appropriate cropping patterns. As a general rule, this cooperation is lacking in many large-scale surface irrigating systems managed in an authoritarian style. The management style is supply-oriented, making water available on fixed schedules, rather than demand-oriented, making water available when needed. The result has been that systems have operated in a wasteful manner and water users have taken extralegal steps to gain access to water when they need it.

A further problem of considerable significance revolves around the trade-offs between providing *some* water to *large* numbers or *larger* amounts of water to *fewer* farmers. The debate centers on helping large numbers to have a modest level of production or enabling fewer farmers to have adequate resources to increase their output substantially. By and large, most of the public-sector projects in South Asia continue a longstanding tradition of spreading water "thinly" to provide large numbers of producers with a modicum of "food security" rather than focusing on maximizing production. The pros and cons of the current approach, along with the ability to modify the existing systems if it is so desired, have yet to be fully studied.

The evaluation looked with favor on users' associations that had a role in 11 of the 21 projects. This role included participating in the operation and maintenance of the projects (notably maintaining canals); in addition, they helped at the margin to ensure equitable distribution of water among the beneficiaries and in some instances to recovering water charges from their members. It is acknowledged that water user associations are no panacea, and the record of their effectiveness has been a mixed one. Nonetheless, the evidence in this evaluation indicates that water users' associations can play an important and constructive role in the planning and management of irrigation systems, and in the decentralization of decision making. There is as yet little experience, though, as to how water user associations can expand their roles to managing whole irrigation systems rather than a local component of a system.

Although this evaluation did not make the point, there is an important issue related to efficiency of water use from a project point of view when compared with a basin-wide point of view. Inefficient and wasteful use of water in a project "upstream" may well benefit farmers "downstream" as the wasted water finds its way into underground aquifers and is used for expanded and pump irrigation. This is indeed happening without too much being known about its consequences for sustainable development.

4.6.5 Water Charges and Revenues

The evaluation of the 21 projects confirms that water users seldom, if ever, pay the full cost involved in delivering water to their holdings, i.e., all water users are subsidized. In some instances, but by no means all, it was expected that charges levied on water users would cover the cost of operation and maintenance, and recover some of the investment cost of the project. All of the projects, with one exception, did use direct cost recovery systems. These varied from volumetric water charges in more sophisticated systems to more generally applied fees payable in kind or cash, and land and water taxes. However, the rates of recovery of these fees, charges and taxes ranged from being "insignificant" to covering the full cost of operating and maintaining a system with up to 40 percent of the cost of the investment in that system. The evaluation emphasized that where the water users were satisfied with the water delivery system and the project authority had a strong commitment to recovering costs, the revenues collected were much higher than when there was poor delivery of water and disinterested central authority.

The issue of water charges continues to be a matter of major importance and concern which would have to be addressed if public-sector projects are "to pay their way" in the future. One widely held view is that public-sector irrigation projects should become self-financing entities, similar to public utilities, and that they should pay themselves by charging for the services they provide to their customers. Over the longer run, establishing water charges subject to competitive market forces is probably the most efficient means of combining the functions of ensuring effective use of water and raising revenues to maintain and operate irrigation systems. For this to be effective though, there has to be a codification of water rights. In addition, there has to be a suitable monitoring system to ensure that the distribution of water is effective and that fees are collected and used for designated purposes.

Whatever the institutional approach, making farmers pay for their water has many beneficial effects. It keeps farmers aware that water is not a free good, but that it has been provided at some cost and should not be wasted. It is a way of reducing somewhat the inequity of income distribution between irrigated and rain-fed areas by recapturing some of the benefits from those who have gained from public investments in irrigation, and to provide some funds which could be specifically set aside for essential maintenance work on the irrigation systems. Most serious studies of irrigation water charges come to the same conclusion, and some insist that putting a price on water is *the* basic requirement for improving the management of water resources. The most appropriate means of measuring, levying and collecting these charges is a question that still begs an answer.

4.6.6 Resource Degradation

There are two major sets of environmental problems that are widespread in many irrigated areas. The most significant is the degradation of the natural resource base — the soil — following the introduction and expansion of irrigation and the intensification of water use at the farm level. In this context, there was an appreciable increase in waterlogging and soil salinity in a number of projects that were reviewed. In two of the surface irrigation projects, poor natural drainage and poor farming practices led to close to 20 percent of the cultivable area being lost to production. In another project that highlights the actual and potential severity of waterlogging and salinity in semiarid areas, the salt-affected area grew from around 800 hectares in 1973 to almost 11,000 hectares in 1987. Some 850 farm families in the project area incurred substantial losses.

The drainage networks inserted into the effected projects to correct salinization and waterlogging were deemed to be highly inadequate or incomplete in close to half of the projects that were examined. Part of the reason for this was the commonly held assumption that drainage would be built after the completion of the irrigation system when there would be a fuller appreciation of the need (or otherwise) for drains. This did not happen.

The spread of salinity and waterlogging has become a significant factor in the degradation in the natural resource base in many parts of the world, most notably in the semiarid areas and in countries such as Pakistan where more than 20 percent of the 35 million hectares of the canal commanded area is said to be "salt affected" [Ahmed and Kutcher 1991]. As has been pointed out above, there is some dispute about the extent of this phenomenon and how much of it is irrigation-induced. Nevertheless, it is a serious problem in a number of localities. Most plans for irrigation works now include some protection against these forms of soil degradation. This adds to the cost of new irrigation, typically 10 percent or more, and makes investment in irrigation projects less attractive when they are appraised using conventional cost-benefit analyses. When such analyses take full account of the savings from introducing drainage, the results may well be different. As yet though, there is little in the way of field studies of the cost and benefits of investment in drainage.

The second major problem of resource degradation that effects irrigation is exogenous to irrigation itself. In many instances, such practices as deforestation on mountain slopes, non-contour farming, and overgrazing lead to soil erosion and loss of fertile top soil. These forms of erosion occur independently of whether irrigation works are constructed or not. However, when erosion occurs in a river basin, the eroded soils not only degrade the natural resource base on the hills, but are transported by winds and rains, adding to the silt in dams and canals being built in the basin. This reduces their efficiency and shortens their effective life.

The implications of high rates of siltation can be serious. The rate of siltation is intricately linked to climate, rainfall, geology, topography and to man's activities. According to one report, India is losing "a staggering two million acre feet of storage capacity in major and medium dams — corresponding to a loss of 700,000 acres of irrigation potential every year" [R.S. Dey 1983]. A 1990 World Bank technical paper described the siltation of 8 dams in India, showing that the rate of siltation is much higher then predicted before construction. The authors conclude that erosion and sedimentation are not only severe and costly but accelerating and that it is essential that greater attention be paid to siltation rates [Doolette and Magrath 1990]. There is also evidence that siltation is reducing the life of dams in parts of Latin America and that erosion in the uplands of countries such as the Philippines is having negative effects on irrigation capacity in the lowlands [Yudelman 1989].

There are remedial actions that can be taken to slow down siltation, including the construction of upstream reservoirs. But, in line with growing concerns about "sustainability," increasing attention is being paid to river basin development to limit erosion. The need for comprehensive river basin planning was demonstrated in one of the projects reviewed by the World Bank's operations evaluation department. In this project, a number of small holders were displaced by the construction of a reservoir; they moved onto hill slopes of the river basin to subsist from unauthorized deforestation. Some ten years later, deforestation and the subsequent erosion had silted up the irrigation canals and had substantially reduced the efficiency of the system. Conceivably, a comprehensive approach — as recommended by the 1992 U.N. Conference on Environment and Development — might have led to a more salutary outcome than occurred when the focus was on building the reservoir.

4.6.7 Health Effects

Irrigation can bring both benefits as well as costs to the health of people living in irrigated areas. Dams, canals, watercourses and drains all can present health hazards. Experience dictates that special attention needs to be given to controlling invertebrates that live or breath in water and transmit the diseases schistosomiasis (spread by snails), onchocerciasis (simulium flies), malaria, arbovirus fever, and filariasis (mosquitoes) [Carruthers 1983]. Prudence requires that every effort be made to minimize the contact between the human population and unprotected water to prevent the creation of man-made breeding grounds, and to ensure that standing water does not exist by improving drains. Irrigation can also create opportunities for benefits by giving the public access to large quantities of high quality water that can be incorporated into rural water supplies. This should help diminish the greatest environmental scourge of all, the spread of waterborne diarrhoeal disease with its debilitating effects on children.

The general experience along the Nile River and elsewhere shows that close cooperation between engineers, agriculturists, and the public health services is essential for dealing with waterborne diseases. This cooperation has not always taken place. In the evaluation of projects financed by the Bank there was a resurgence of malaria in one particular project area. This was attributed to increasing resistance by malarial mosquitoes to chemicals used as pesticides. Without adequate precautions, this could well lead to a "treadmill" effect whereby increasingly toxic chemicals are used as mosquitoes become increasingly resistant to each stronger chemical. The increase in the toxicity of chemicals would have additional debilitating effects on the community using them. In the particular case that was examined, it was suggested that the elimination of breeding grounds for the mosquitoes, along with promoting integrated pest management requiring less chemicals, could well be a preferred option for controlling malaria.

This project also highlights the problems that can arise from the intensification of agricultural production as a result of the introduction of irrigated agriculture. When the intensification of agriculture leads to excessive use of agro-chemicals, this can worsen the quality of water used both for irrigation and for drinking. The longer-term impact on potable water supplies becomes more serious when, as has happened, the agro-chemicals seep into the aquifers that provide drinking water for villages. In addition, excessive use of chemicals can have harmful effects on the ecosystem, especially where poisoned water destroys fish and wildlife.

4.6.8. Social Impact

One of the projects evaluated included "involuntary displacement" of small-scale and poor farmers to make way for the construction of a reservoir that would benefit a large number of producers downstream. In this particular project, no special provision was made for the compensation or resettlement of the dispossessed. Since the time when this particular project was initiated (1976), most aid agencies have modified their policies to ensure that due account is taken of the impact of projects on displacing people and that the displaced should be compensated for their losses.

The issue involved in this project and similar projects can be viewed largely as one of social equity and human rights associated with the displacements arising from large-scale irrigation projects. It is not an environmental problem *per se*, but rather the more familiar one of balancing gains to the economy as a whole with the costs to others that are displaced by the project. Many critics contend that the issue of involuntary settlement arises because of a bias in favor of large-scale dams, and an indifference about the fate of the poor, including indigenous tribal groups who have little to say in the decisions that are made about inundating or sequestering the land they use for their subsistence [Pearce 1992]. The role of large-scale dams is open to debate. Dams will be built, and there will continue to be difficult problems arising from resettling the displaced, including the problem of developing alternative sites for their use. This will not be an easy task, especially in densely populated areas such as in India where the development of the Narmada River calls for the compensation or resettlement of more than 600,000 "oustees." Similarly, the resettlement of millions displaced by the Three Gorges Project in China will have to take place in densely populated areas.

There are many other socioeconomic issues that arise in the implementation of irrigation schemes. There has been a great deal written about the problems of ensuring greater equity in the distribution of water in large surface irrigation systems [Wade 1982]. There has also been increasing interest in the impact of irrigation on the lives of women. The 21 projects evaluated were reported to have had a mixed impact on the lives of women and children: some projects increased women's workloads with little increase in compensation, while in others, a stable labor force was able to earn more and invest more in items such as improved houses. Other socioeconomic concerns include the effects of irrigation on income distribution and tenure [Hazell and Ramasamy 1991]. By and large, though, there has yet to be any cross-sectional analysis about the impact of irrigation on the lives of water users especially women in different agro-climatic zones and in different cultures and water regimes.

The "low" returns on capital, problems of operation and maintenance, low efficiency of water use, low levels of water charges and low revenues, the spread of soil salinity and siltation, problems of health and resettlement of displaced persons have lessened the enthusiasm for expanding irrigation. These concerns also indicate some of the major issues that need further investigation and that have to be addressed to make existing systems more effective, a necessary requirement if yields are to be raised to meet the projected demand for food production in the years ahead.

4.7 POTENTIAL FOR EXPANDING IRRIGATION

There have been several estimates of the physical potential for expanding irrigation. Most of these estimates are based on criteria that center on agroclimatic conditions where controlling water would lead to increased output from productive but underutilized soils. The estimates that have been made suffer from the limitations of available data. There are wide differences in some of these estimates, e.g., FAO estimated that there are 3.5 million hectares of land available and suitable for irrigation in Zambia while the World Bank estimates that the potential is only 12 percent of that amount or 420,000 hectares [Olivares 1987]. Most of the estimates, though, agree that there is scope for expansion (though some countries, in areas such as the Middle East and North Africa, are beginning to reach the outer limits of expansion from available water supply).

There is potential for further expansion among the countries with the largest areas under irrigation. In India, an estimate made by the government in 1981 indicated that the ultimate potential for irrigation was 113.5 million hectares of which 45.6 million hectares were unexploited. This figure however did not include the potential for expansion from what would be very costly interbasin transfers of water from water-surplus areas to water-deficit areas, which could well add a further 25 million hectares to the total potential. Similarly, in China, there is still a potential for large-scale expansion of irrigation though far less than in India. According to privileged sources, China has the potential to irrigate 60 million hectares or around 25 percent above the current area irrigated. This does not include the potential from the south-north transfer of water from the Yangtze River Basin to the Yellow River. Nor does it include very large areas of degraded lands that could be made suitable for irrigation in the future.

There is also potential for expansion in many of the smaller countries of the world. A study that included seven countries in Sub-Saharan Africa concluded that from 4 percent to 67 percent of the irrigated area in each country was being exploited and that irrigable area could be expanded fourfold. Within the region, only the Sudan is anywhere close to exploiting more than two thirds of its potential.

One comprehensive estimate of the overall potential for expansion in the developing countries prepared by the World Bank and the UNDP concludes that there is scope for a 59 percent increase in area under irrigation in the developing countries as a whole [see Table 4.5]. The largest potential for increase (69 million hectares) is in Asia, especially in India and China. This is followed by South America with 20 million hectares, mostly in Brazil. Sub-Saharan Africa has a potential to increase its irrigated areas by more than 470 percent, from a reported 3.4 million hectares to 16.5 million hectares, the largest potential increase being in Angola. The most limited opportunities for expansion are in the Middle East, Central America and North Africa.

On the face of it, there appears to be considerable scope for expanding irrigation. Theoretically, an expansion of 110 million hectares could provide an additional 300-400 million tons of grain or enough to provide the basic diet for between 1.5 billion to 2 billion people. Based on current trends, though, this would require an investment of $500-1,000 billion. Further, as is pointed out below, the potential appears to be inadequate to sustain recent rates of expansion beyond 2025.

4.8 CONCLUSION: THE IRRIGATION POTENTIAL

The expansion of irrigation has been a major factor in the rapid growth of food production in 1960-90. During those years, irrigated area grew from 100 million hectares to more than 170 million hectares. Irrigation has been especially important in the production of high-yielding varieties of rice and wheat (with 57 percent of the value of these two most important cereals being produced on irrigated lands). About half of the irrigated area is in the arid, semiarid or Mediterranean agroclimatic zones where there are limited alternatives for crop production without irrigation.

There are many problems associated with the implementation of irrigation projects. These include: low returns on investment, poor maintenance, low efficiency of water use, low collection of water charges, degradation of resources, health-related issues and negative social impacts (including the distribution of gains from irrigation projects). Many of these problems can be ameliorated by changes in policies and approaches to dealing with water-related issues.

The expansion of irrigation has been impressive; but if past rates of increase in the expansion of irrigation are continued, then the prospects are that the available potential will be exhausted well before 2050. This is most notable in the case of Asia, the region most dependent on irrigation for its food supply. Between 1960 and 1990 the area under irrigation grew from 87 million hectares to 147 million hectares , or at a rate of 1.82 percent a year; the rate of growth slowed down between 1980 and 1990 when the area under irrigation rose by 1.26 percent a year, from 129 million hectares to 147 million hectares. The World Bank/UNDP estimates that a potential exists to irrigate 228 million hectares. If irrigation were to expand at the same pace as it has over the past 30 years then all irrigation potential will be exhausted by 2015; if it expands at the much slower rate of the last decade then the potential will be exploited by 2025 [see Figure 4.2].

The prospects of a limitation on the expansion of irrigation in Asia is disconcerting as the increase in irrigation in that region has been one of the engines of agricultural growth. It is probable that rising costs will slow down irrigation expansion well before the limits are reached. This will raise the premium on improving the efficiency of *all* irrigated agriculture to meet future demand.

There is potential for increasing the area under cultivation in all the regions of the tropics. The biggest *pressure* for expanding irrigation is in the land-scarce countries of Asia where there are limited prospects for increasing yields in nonirrigated areas. All in all, it is probable that irrigation will expand at a slower rate than in the 1960s and 1970s but at a rate closer to that in the late 1980s when the rate of expansion had slowed to an additional one to two million hectares a year. In this event, area under irrigation will expand to between 205 million and 240 million hectares by 2025.

A slower rate of expansion of irrigation would make it necessary to improve the efficiency of existing irrigated systems if yields are to be increased as needed in the future. This will include improving the timeliness of irrigation deliveries to farmers, saving water through greater efficiencies in conveyance and ensuring that the saved water is redistributed to be used effectively, and reducing losses from salinity and waterlogging. The combined effects of improving efficiencies could lead to substantial production benefits. In the future too, improved conveyance efficiency will have to be accompanied by improved use of water at the farm level. Over the long run, this could well involve changing on- farm technologies as well patterns of production to use scarce irrigation water on less-water-intensive crops. These requirements pose a great challenge to institutions such as IIMI that have a mandate to help improve the effectiveness of irrigation systems so that irrigated agriculture will make the fullest possible contribution to meeting the needs of the 8 to 10 billion inhabitants in the developing countries in the middle of the next century.

Table 4.1. Distribution of Irrigated Land by FAO Regions and Agroecological Zones (in million ha).

Zone	Total	Asia	Sub-Saharan Africa	West Asia & North Africa	Latin America & Caribbean
Warm arid and semiarid tropics	27.70	22.15	3.69	0.10	1.76
Warm subhumid tropics	10.29	7.70	0.43		2.16
Warm humid tropics	16.74	14.50	0.44		1.80
Cool tropics	2.93		0.66	0.25	2.02
Warm arid and semiarid subtropics with summer rainfall	45.61	43.02			2.59
Warm subhumid tropics with summer rainfall	10.61	10.14			0.47
Warm/cool humid subtropics with summer rainfall	23.91	22.77			1.14
Cool subtropics with summer rainfall	15.57	15.47			0.10
Cool subtropics with winter rainfall	20.34			18.31	2.03
Total	173.70	135.75	5.22	18.66	14.07

Source: TAC 1992.

Table 4.2. Developing Countries with an Irrigated Area of more than 100,000 ha.

	Irrigated area in '000 ha	Percentage of cropped land that is irrigated		Irrigated area in '000 ha	Percentage of cropped land that is irrigated
East + South Asia			*Latin America*		
China	45,349	47	Mexico	5,150	21
India	43,039	27	Brazil	2,700	3
Pakistan	16,220	75	Argentina	1,760	5
Indonesia	7,500	36	Chile	1,265	29
Thailand	4,230	20	Peru	1,250	33
Bangladesh	2,738	24	Cuba	896	26
Vietnam	1,830	28	Ecuador	550	20
Philippines	1,620	19	Colombia	515	10
South Korea	1,400	64	Venezuela	264	9
North Korea	1,353	50	Dominican Republic	225	15
Myanmar	1,010	10	Bolivia	165	5
Nepal	943	28	Guyana	130	26
Sri Lanka	560	29	El Salvador	120	16
Malaysia	342	7	Costa Rica	118	22
Laos	120	13			
Middle East + North Africa			*Sub-Saharan Africa*		
Iran	5,750	30	Madagascar	900	29
Afghanistan	2,660	33	Nigeria	865	3
Egypt	2,585	100	Zimbabwe	220	8
Iraq	2,550	47	Mali	205	10
Turkey	2,220	8	Senegal	180	3
Sudan	1,890	15	Ethiopia	162	1
Morocco	1,265	14	Tanzania	155	3
Syria	670	12	Somalia	116	11
Saudi Arabia	435	15	Mozambique	115	4
Algeria	336	5			
Yemen	310	21			
Tunisia	275	6			
Libya	242	11			
Isreal	214	40			

Source: FAO Production Yearbook 1990.

Table 4.3. Estimates of Value of Food and Agricultural Crop Production and Percentages Grown in Developing Countries on Irrigated Land in 1988-89.

	Value (billions dollars)		Percentage grown on irrigated land
	Total	Irrigated	
All crops	364.2[1]	104.1[2]	28.5
Food crops	310.8	96.1	30.9
All grains	148.3	69.1	46.5
Rice and wheat	117.1	67.1	57.1
Wheat	31.1	15.5	50.0
Rice	85.9	51.6	60.0

[1] TAC.
[2] Author's estimates.

Table 4.4. Irrigated Area, 1961-90 (1,000 ha).

	1961	**1962**	**1963**	**1964**	**1965**	**1966**	**1967**	**1968**	**1969**	**1970**
South America	4,580	4,673	4,789	4,861	4,949	5,110	5,207	5,301	5,410	5,579
Asia	87,330	88,916	90,621	92,311	94,330	96,288	98,404	100,729	103,791	106,452
Africa	7,795	7,795	7,847	7,931	8,205	8,390	8,518	8,599	8,724	8,821
North and Central America	3,608	3,699	3,783	3,864	3,954	4,040	4,128	4,266	4,414	4,534
	103,313	105,083	107,040	108,967	111,438	113,828	116,257	118,895	122,339	125,386
	1971	**1972**	**1973**	**1974**	**1975**	**1976**	**1977**	**1978**	**1979**	**1980**
South America	5,759	5,929	6163	6344	6,519	6,699	6,868	7,053	7,218	7,401
Asia	108,579	110,758	114,006	115,861	118,577	121,012	123,445	126,476	128,495	129,335
Africa	8,973	9,073	9,222	9,354	9,488	9,575	9,655	9,743	9,836	9,999
North and Central America	4,751	5,045	5,219	5,424	5,663	6,084	6,212	6,292	6,420	6,509
	128,062	130,805	134,610	136,983	140,247	143,370	146,180	149,564	151,969	153,244
	1981	**1982**	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**
South America	7,581	7,736	7,898	8,036	8,207	8,362	8,257	8,687	8,835	8,775
Asia	130,988	132,589	134,542	137,112	139,621	140,243	142,031	143,266	145,022	147,403
Africa	10,146	10,281	10,435	10,573	10,740	10,929	10,997	11,103	11,186	11,273
North and Central Amercia		6,593	6,675	6,486	6,563	7,015	6,936	6,866	6,887	6,978
	155,305	127,281	159,361	162,284	165,583	166,470	168,151	169,943	172,021	174,461

Table 4.4a. Increase in Total Irrigated Area over Previous Year.

Percentage Increase

	1962	1963	1964	1965	1966	1967	1968	1969	1970
	1.71	1.86	1.80	2.27	2.14	2.13	2.27	2.90	2.49
1971	1,972	1,973	1,974	1,975	1,976	1,977	1,978	1,979	1,980
2676	2,743	3,805	2,373	3,264	3,123	2,810	3,384	2,405	1,275
1981	1,982	1,983	1,984	1,985	1,986	1,987	1,988	1,989	1,990
1.34	1.27	1.32	1.83	2.03	0.54	1.01	1.07	1.22	1.42

Increase in 1,000 ha

	1962	1963	1964	1965	1966	1967	1968	1969	1970
	1,770	1,957	1,927	2,471	2,390	2,429	2,638	3,444	3,047
1971	1,972	1,973	1,974	1,975	1,976	1,977	1,978	1,979	1,980
2676	2,743	3,805	2,373	3,264	3,123	2,810	3,384	2,405	1,275
1981	1,982	1,983	1,984	1,985	1,986	1,987	1,988	1,989	1,990
2061	1,976	2,080	2,923	3,299	887	1,681	1,792	2,078	2,440

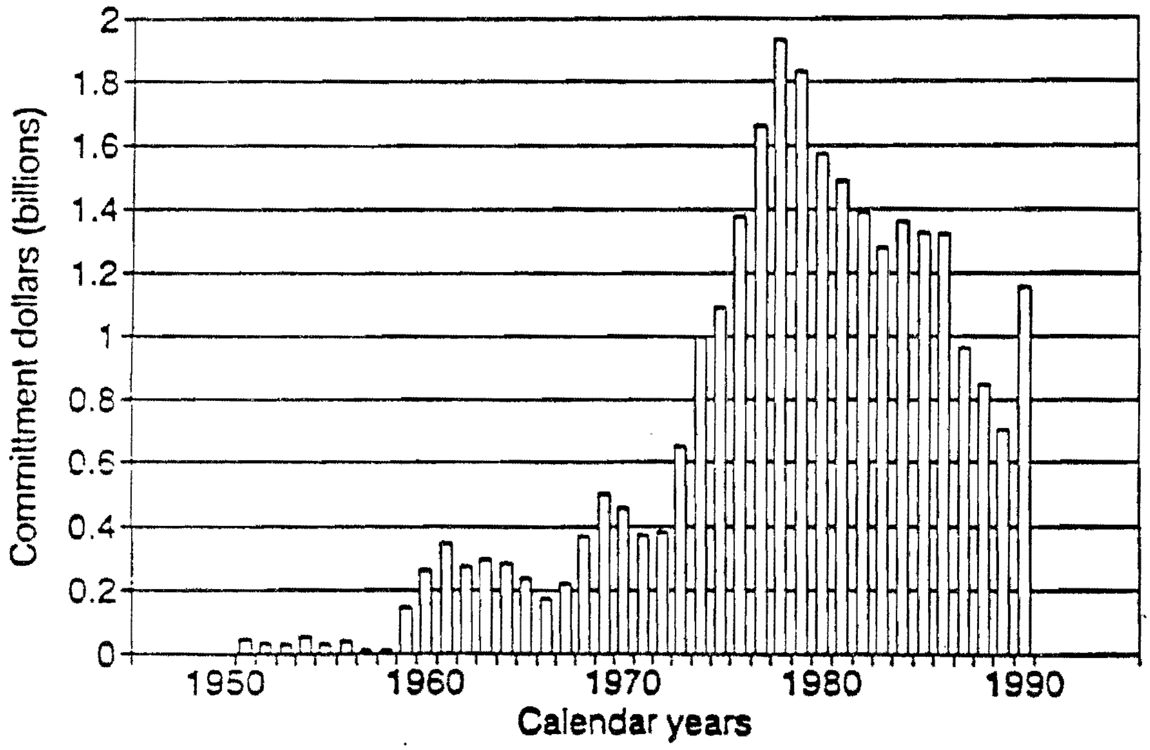
Source: FAO AGROSTAT Data Base 1992.

Table 4.5. Presently Irrigated Land and Land with Irrigation Potential.

	Presently irrigated	Potentially irrigable	Potential increase
	1,000 ha		percent
Less-developed countries	186,000	110,500	59
Global			
Africa	11,025	18,175	165
North	7,560	1,640	22
Sub-Saharan	3,465	16,535	477
Latin America	16,235	22,865	141
North and Central	7,035	2,865	41
South	9,200	20,000	217
Asia	58,380	69,420	44
Near East (Middle East)	18,315	5,185	28
Far East	40,065	64,235	46

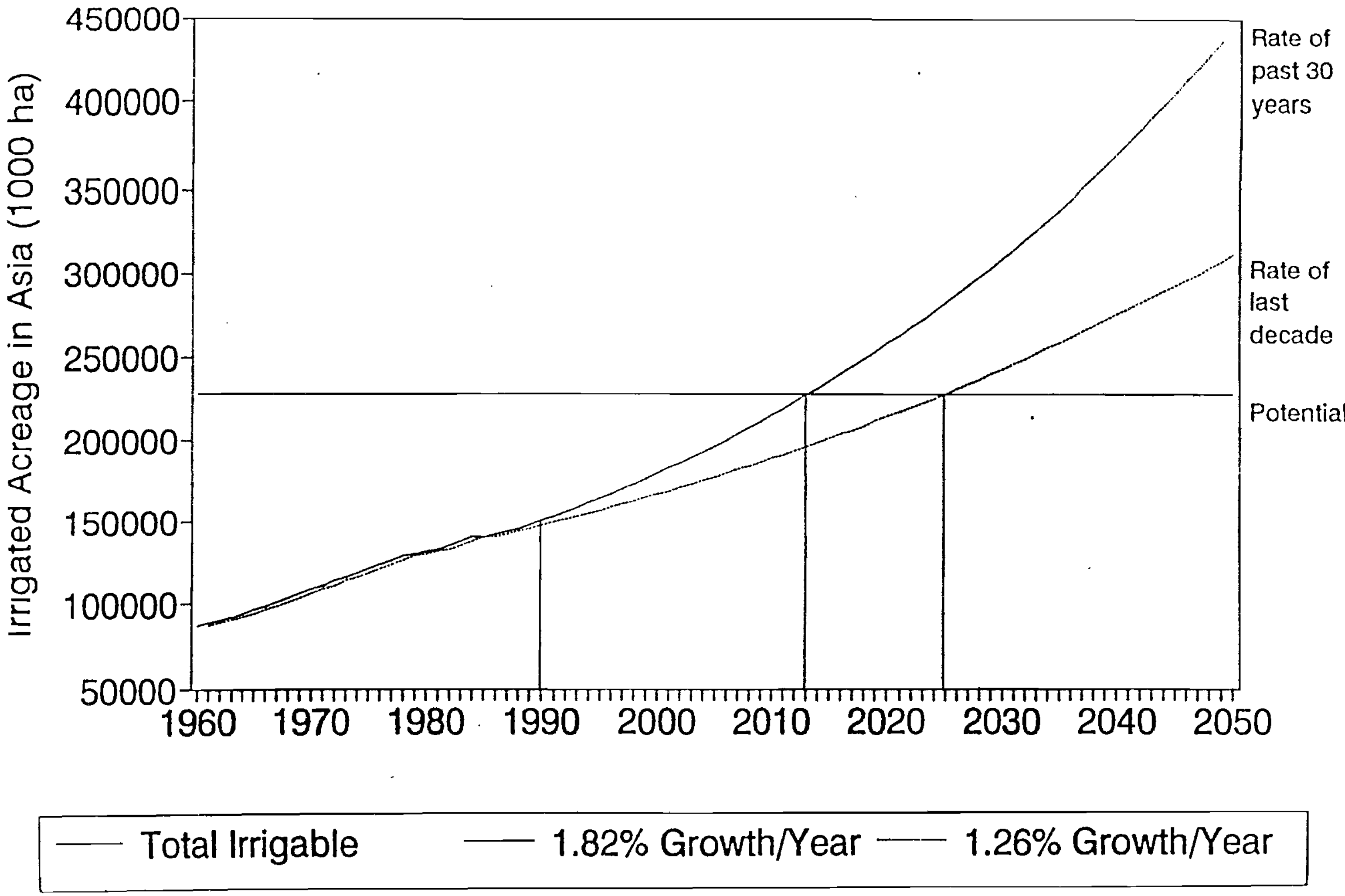
Source: World Bank/UNDP (1990).

Figure 4.1. World Bank Irrigation Lending (constant 1991 dollars, 3 year MA).



Source: World Bank, OEDO.

Figure 4.2. Irrigated Acreage Expansion in Asia against potentially Irrigable Land.



CHAPTER V

Irrigation Research Topics

5.1 SCOPE OF RESEARCH

The proposals for research do not constitute a research agenda as such; rather, these proposals are presented as *suggestions* on topics which are "researchable" and which bear on some of the major issues that link irrigation with increasing food production in a sustainable manner. The proposals have emerged in part from the analysis in the first part of this paper and the author's own experiences. The suggestions are intended to be pragmatic and in line with what is perceived to be IIMI's comparative advantage — access to information from a large number of different sources, and the opportunity to undertake action research in the field with cooperating partners. The overall orientation is toward a combination of obtaining a better understanding of how the irrigated sector performs, anticipating some of the major issues of the future, and identifying what might be done to improve irrigation management in the light of changing circumstances in the years ahead.

The research topics themselves are divided into two parts. The first deals with sector-wide issues and is akin to a "think-tank" type of operation that relies largely on secondary data; the second focuses on case studies which depend largely on action research that generates primary data.

The first part of this report made it clear that a number of important issues may influence the supply of water in different localities in the future. These issues include:

a. the effects of climate change and global warming on the supply of moisture in different locales;

b. the costs of desalination and the possibilities of augmenting the supply of water from this source; and

c. the impact of changes in international treaties on national rights to water.

IIMI has no comparative advantage in doing research on these issues. However, as a research institute concerned with the future role of water in agricultural production, IIMI should keep a monitoring brief on these and related topics that fall beyond IIMI's immediate purview.

5.2 DATA PROBLEMS

At the outset, it has to be emphasized that the poor quality of data is a major drawback in any analysis of the performance of irrigated agriculture and its future needs. While improving the quality of data may not be essential for increasing food production, the absence and unreliability of data make it difficult to monitor changes that have taken place as well as to develop a vision and a strategy for the future development of water resources and the role of irrigation in increasing food production.

It is very disappointing to find how little progress has been made in improving the quality of information and data on natural resources in the developing countries over the past forty years. This applies with special force to water-related issues, which may be especially problematic because of the "fluidity" of water, e.g., the areas that receive supplemental irrigation wax and wane in line with annual variations in rainfall. There are shortcomings in the most basic primary data such as the extent of area under irrigation, the number of hectares actually irrigated, the intensity of irrigation, the extent of soil salinity and waterlogging, the number of tubewells in operation, and so forth.

International estimates of relevant data are assembled by FAO and ICID on the basis of information provided by national governments. One difficulty in aggregating national estimates is lack of standardization of reporting. Furthermore, the data that are presented by a number of national authorities tend to be unreliable (to the author's own knowledge, in at least two countries with substantial areas covered by irrigation, different departments in the same government give entirely different estimates of similar measures such as "area under irrigation"). There is also widespread recognition that there are deliberate distortions in reporting increases in the growth of irrigated lands, both at the local and regional level, to show progress to appease donors and to satisfy politicians.

The problems of improving data are compounded by two factors. The first is that most national and international agencies responsible for assembling data are under-funded. Collection of data is accorded low priority by national and state governments and by international agencies and donors. Secondly, up until the present time, the promise of new technology including satellite imagery and geographic information systems (GIS) have yet to come to fruition. Hopefully this will change over time.

One point that deserves to be noted is that the questionable nature of some of the data makes the testing of some hypotheses more a matter of getting factual information than undertaking original or applied research. There is a widely cited hypothesis that more land is being lost every year from irrigation-induced salinity than is being added from expanding the area under irrigation. At present this hypothesis cannot be tested in any meaningful way because of the crude nature of the available data. This is made clear by the incredibly wide range of estimates of land "lost" to salinity in recent years. Only when the available national data are improved or when a special survey is undertaken to gather data for this purpose, will it be possible to show where this might be true, and where it might not be true and the extent to which irrigation is sustainable or non-sustainable. Until then the statement about the loss of land from salinity is open to question as is the issue about the priority that should be given to dealing with land reclamation compared with extending the area under irrigation.

The issue of improving available information on water resources and irrigation is complex. But there is a growing recognition of the importance of doing more than is presently being done to improve information about natural resource management, including the management of irrigation. The recent UNCED conference confirmed this. Consequently, *it is strongly recommended that IIMI should contribute to improving the database on irrigation and related issues.* This could be done by undertaking special projects in collaboration with other institutions. In addition, several of the research programs outlined below focus on improving information. Subsequently, IIMI might convene a meeting among interested parties as a first step toward devising means to improve data gathering and particularly implementing any program that might emerge from such a meeting. Acquiring data and a greater knowledge about the present situation (and the problems encountered in developing irrigation) are among the necessary preconditions for understanding past problems and redressing them in the future.

5.3 SECTORAL ISSUES

5.3.1 Performance Indicators and Assessment

There have been a number of evaluations of irrigation projects by international agencies, bilateral donors, and some governments. These analyses, such as those discussed in section 4.6, confirm that many projects operate at sub-optimal levels. Criteria used are based on the evaluating institutions own judgements as to what indicators should be included in any evaluation, e.g., the economic rate of return, the effects on the environment, water efficiency, and so forth.

Evaluations at the project level have served a useful but limited purpose. In this context "lumping together" evaluations of irrigation without differentiating among different environments can be misleading; for example, in the Middle East, water is the scarce factor, while in Bangladesh, land is the scarce factor. There is a need for systematic comparative analysis of the performance of different irrigation systems operating in different agro-ecological zones. Such performance evaluation could well establish different typologies of irrigation systems, and then based on these typologies establish criteria for judging performance. Thereafter, there would have to be a substantial, concerted effort to gather data and to analyze these data in line with the criteria to be used for evaluating the effectiveness of irrigation systems. The data-gathering exercise in itself could add a great deal to the available information about the irrigated sector.

The preliminary work for an undertaking of this kind has been done at IIMI. There has been progress in creating a framework for setting up the criteria to evaluate the impact of different irrigation systems. The proposed criteria to be used are interdisciplinary and go well beyond the more usual evaluations by donor institutions. These criteria include such "normative indicators" as technical efficiency, manageability, reliability, flexibility, equity, and water quality, as well as composite indicators of production, net income, return on investment, and employment generation. These criteria cover all stages of the irrigation system.

Completing this work and applying it to ongoing systems will be a major undertaking. Ultimately, the test of this work will be in how well it can provide guidance for planners and managers of irrigation systems in their task of using available resources more efficiently and increasing food production in the future. This will depend, inter alia, on introducing a systematic management cycle and the incentives to use the information generated by the indicators. Thus the process of how information should be used is as important as generating the information itself.

IIMI will make a substantial contribution to improved water use if it succeeds in developing suitable indicators, promoting their acceptance and ensuring their use as management tools. This will be no easy task but its accomplishment can lay the groundwork for much needed improvements at all levels of irrigation systems.

5.3.2 Institutional Capacities and Sector Management

There is a clear need for a better understanding of what IIMI terms "institutional capacities and sector management" as factors contributing to why irrigation sub-sectors (and, where appropriate, irrigation systems) are operated below attainable standards (based on current available performance indicators). The scope of any inquiry into matters of this kind could range from examining the impact of exogenous factors such as the system of allocating foreign exchange on irrigation maintenance to endogenous factors such as the "style of management," and problems of communications amongst officers dealing with water supplies in large irrigation systems. Whatever the scope, the aim will be to understand what prompts managers to make the decisions that they do make, whether these decisions be at the center or at a decentralized level.

There are at least two reasons for supporting research of this kind. The first is that it is widely accepted that irrigation systems are operating below attainable levels. Often — by no means always — there are identified bottlenecks that inhibit improved performance. Despite this, experience indicates that the systems continue to operate as they have in the past even though managers are aware of what is needed to improve their operations. Consequently, there is need to look into the reason why governments (and others) do not adopt the identified solutions for improving the efficiency of their systems. The inquiry might point out what can be done within existing constraints to change this state of affairs.

The second more general reason for an inquiry of this kind is that management at all levels has to be able to adapt to radical changes that are taking place in the public and private sectors in different parts of the world. These changes include new roles for the government, strengthening of government institutions, privatization of government organisations and services, budget constraints, and decentralization of management responsibilities by removing them from the center to the field. There is also a growing concern about the environment and renewed interest in issues of equity. All these concerns call for changes in the mode of management of both public and private sector irrigation that might have been satisfactory in earlier years but is unable to cope with current and future needs. There is still much to be learned about processes which are best suited to the changes that will be required in the future.

IIMI has started to examine some of the problems in developing institutional capacity and improving sector management in several countries. This is a very large topic that requires selectivity in choosing points of entry into a research program. But it is important that there be progress in this general area as it deals directly with the central *raison d'etre* of IIMI's existence: the improvement of irrigation management to enhance the performance of the irrigated sector.

5.3.3 The Potential for Expanding Output from Irrigated Lands

If the land under irrigation continues expanding as in the past 30 years, then it is possible that all potentially irrigable land will be in use by 2025. Can irrigation expand by anywhere up to and beyond 50 million hectares by 2025, mostly in Asia, but also in Africa? This issue is at the heart of any global view of the future role of irrigation in meeting demand. It involves two subsets of questions. The first relates to the opportunities for the expansion of irrigated agriculture and could best be framed by the hypothesis that future development of irrigation will require substantial investments that would be difficult to justify. The question is whether there are opportunities for the expansion of irrigation that can be justified on the basis of acceptable economic criteria (or should the criteria be modified?). It is widely held that most of the "best-situated sites" for impounding water have been developed, and that the real costs of developing new sites are very high (while the prices for output have not increased over the last decade). There is widespread acceptance of this view which is adding to pressure to focus investment on improving existing facilities. This view should not be accepted without rigorous examination.

The issue of potential for expansion is all the more vexing because aggregate data from FAO and the UNDP indicate that there is still scope for expanding the areas under irrigation. It may well be that the question of potential for expansion revolves around concepts and the quality of data. Substantively, though, much more needs to be known about the economic feasibility of any expansion, the capital costs involved, and the probable returns on such investments, as well as the likely impact on food security and employment.

The idea of knowing more about the potential for expansion of irrigated area has merit. Any analysis, though, would represent an ambitious undertaking. It would have to start with developing a framework for analysis, then testing the feasibility of using this framework. The initial estimates developed may will be approximate but they will undoubtedly be an improvement on existing estimates. There may well be merit in testing the feasibility of determining what the potential for future expansion is, by starting in one area where there is said to be considerable unexploited potential. The results of such an analysis could serve as a basis for determining whether the exercise should be extended.

Parallel to the examination of the potential for expansion of area is the need to know much more about the possibilities of increasing yields on existing lands under irrigation. This is especially important since most of the future increase in production will come from raising yields per hectare per year off irrigated land.

The international centers, such as IRRI and CIMMYT, focus on yield increases from a commodity-oriented point of view. What appears to be lacking is a better appreciation of the potential for increasing total output of irrigated lands under field conditions. A case in point is the large wheat-rice rotations in South Asia and China where yields appear to be below attainable levels. There is a great deal of scattered data and information that could be assembled and analyzed to give a better insights of what could be attained, and how improving the management of moisture could help raise yields in the future.

5.3.4 Urbanization and irrigation

The UNCED, the Dublin Conference, and the World Bank's Policy Paper on Water have all stressed the importance of taking a holistic view of water-related problems: water should be viewed inter-sectorally as well as intra-sectorally.

In this context, note has to be taken of the current competition for water in some semi-arid areas (North Africa and the Middle East) and in specific locations around large cities in different parts of the world. Note also has to be taken of the demographic projections that foresee a very large increase in urbanization and the growth of "megacities" by the first quarter of the next century.

The context of the proposed analysis would depend on the findings of an initial survey to test the hypothesis that competition for water is limiting the expansion of irrigation in some areas and will be an increasing problem in the future.

The issues that might then be addressed are:

a. Is the growing competition confined to the drier agroclimatic zones or is it a more universal problem? Will the competition for water be "segmented", i.e., will the impact of urbanization have an impact on the urban "hinterland" or will it lead to a more general competition for water? In other words, how much will the growth of Mexico City or Karachi effect local, regional or national supplies of water for irrigation?

b. If there are growing competitive pressures and growing demand from different sectors, what mechanisms are best suited for redistributing water and how can this demand best be managed to "optimize" the use of water in the future? When would rationing be appropriate and how can inter-sectoral markets be made to work effectively? Can such markets be created without substantial changes, e.g., changing the legal rights of producers and consumers, codifying rights to water, etc. etc.

c. The general assumption is that water will have to be allocated away from agriculture to urban/industrial use; this raises a number of issues about how irrigation can be made more efficient and what this would mean, not only for improving efficiency of water use but for resource management within agriculture. Would this add to pressure to cultivate non-irrigated land? Would countries that rely heavily on irrigated agriculture — such as Egypt and Pakistan — have to make changes in cropping patterns toward less "water intensive" crops and what would that imply for agricultural development and agricultural trade?

d. Given that rapid urbanization will take place, is it possible, and economically feasible, for urban waste water to be recycled for use on cropland? Can low-quality water from urban areas be used to grow food and other high unit value crops in the vicinity of urban areas instead of being dumped in rivers with harmful consequences for health? Could the extensive recycling of water open a market whereby farmers sell potable water to urban water users and buy low quality water, suitable for use in agriculture, from the urban sector?

Basically the issues proposed relate to demand management rather than supply augmentation. Demand management will become increasingly important as pressures grow on available water resources. Obviously the sector that will be most affected by the reallocation of water will be the irrigated sector.

5.3.5 Large Schemes and Small Schemes

It is likely that, despite the claim that low-cost options have been exhausted, there will have to be an extension of the area under irrigation including the development of some large-scale schemes. There is an almost visceral reaction by most environmental groups against the development of large-scale systems. This has been demonstrated by the recent international debate over the damming of the Narmada River.

There appears to be a general agreement that the development of large-scale irrigation systems should be avoided when there is a reasonable alternative choice, partly because of the risks involved in having large sunk costs in the face of uncertain environmental and other outcomes. However, a policy to develop only small systems might slow down the pace of development of irrigation and so *may* turn out to be more costly to the economy in the long run. Large river basins may not be amenable to development into a number of small basins. Economy of scale will continue to be an important factor in large reservoirs which are often part of a multi-purpose project, in which electric power generation is a major component. It is very much an open question whether system management problems can be eliminated or reduced and system performance improved substantially when scaling down the size of systems. It is also and open question whether a large project, by its very nature, will cause irreparable environmental damage or more damage than a large number of smaller projects that will be more difficult to "regulate."

Increasing food production will require some expansion in irrigation. Given the likelihood that there will be a need for large-scale inter-basin transfers in the future, it is important that there be some analysis of the optimal size of systems. The optimal size should take account of alternatives in the capacities for planning, implementing, and maintaining the systems. Ecological and environmental considerations which have been neglected in the past should also be considered.

The recommendation is that there be research on typologies of systems and a discussion of criteria that could be useful in clarifying the issues involved. It is strongly recommended that work should be done on this topic but that it should be done in cooperation with appropriate environmental groups.

5.4 ACTION RESEARCH

5.4.1 Equity and Productivity in Large-Scale Surface Systems

Issues involved in improving the management of large-scale irrigation systems, such as those in South Asia, are immensely complex. They involve questions about the effectiveness of the hierarchical structure of management that attempts to control water supplies from the water source all the way to the farm turnout. They involve technical issues, such as the relative lack of control structures, the length, depth and size of tertiary canals, the lack of proper information monitoring and feedback systems, and a basic design conflict between the need to serve a large number of users in contrast to providing an optimal quantity of irrigation water to a smaller set of users. They involve constant tension between the suppliers of water, who often see their role as providers of water according to a strict schedule, and the users, who want water available on demand to meet the requirements of their specific crop mix. They also involve problems of equity, particularly between head enders and tail enders within the large systems, as well as the incentives for extracting rent created by vesting control of the valuable water in the hands of individuals that are not answerable to their clients, the water users.

Recognizing that the large irrigation systems have not been performing up to expectations, and driven by the fact that governments are being forced to reduce their overall budgets including subsidies to the agricultural sector, many governments are now implementing programs to transfer additional responsibility for management to local organizations of water users. In large irrigation systems, management transfer leads to a system of joint management where the public agency retains control of the water source and the main distribution canals while the water user associations are given responsibility for the management of water supplies on the secondary and minor canals and within the distribution block, and of course on the farm.

Management transfer is clearly designed to transfer much of the burden for O&M to the users, thus reducing the demands on the national budget. There is also an expectation that local management of irrigation systems will increase equity and efficiency of water use as well as generating higher productivity. This would then allow the water users to cover their increased water costs out of rising farm incomes. If organized properly, jointly managed systems should be less costly per unit of water delivered in contrast to systems that are totally publicly managed systems.

Research results have demonstrated that, under the proper circumstances, jointly managed irrigation is more responsive to local requirements and thus more equitable. Determining what these circumstances are for different type irrigation systems is a research challenge for IIMI. To meet this challenge, IIMI should design research programs to test alternative approaches to irrigation management, including joint management and management transfer programs. Although difficult, generating greater knowledge about the costs and benefits of the trade off between various management approaches will help managers and administrators as they consider alternative ways to more equitably and productively manage large-scale irrigation systems to meet future food requirements.

5.4.2 Drainage

There is a great deal of concern about the spread of irrigation-induced salinity. In the past, little attention was paid to including drainage components as part of irrigation projects. However, in recent years there has been growing recognition of the importance of good drainage as a factor in limiting the spread of waterlogging and salinity with a debilitating impact on crop production. Currently, most irrigation projects include provisions for installing drains, should this be necessary.

Managers need to know more than they do at present about the options that are open to them regarding investments in drainage facilities. They need to know about the optimal type of drains for different soils, typography, and crop programs, as well as the optimal timing of installing draining to reduce losses. They also need to know what kind of drains will give the best economic returns, sub-surface drains, mole drains, tile drains, earth-and-gravel drains, or perforated plastic pipes, etc. Analysis of these issues will involve more than traditional cost/benefit approaches as, apart from the question of the optimal timing of the investment, there will have to be some estimate of the "losses prevented" from investments in improving drainage facilities.

The problems of waterlogging and salinity appear to be increasing; there is concern about soil degradation and the sustainability of production. In the future, irrigation will have to expand to meet food demands, and yields will have to be raised on existing irrigated lands. A better understanding of the options and the timing and valuing of the costs and benefits of drainage can help managers in their quest to increase output of irrigated lands in a sustainable manner.

Unfortunately, it appears that a shortage of resources is limiting IIMI's opportunities to make a contribution in this area of water resource management.

5.4.3 Project Preparation

Evaluations of project performance indicate that poor project preparation is a most important reason for project failure. In the evaluations, poor preparations are said to be largely a result of making overly optimistic assumptions, frequently based on incomplete information about the natural resource base, including the availability of water.

Since project preparation is such an important element in determining the success or otherwise of a project, it is important to learn more about the assumptions made when projects are prepared, and the extent to which and reasons why these assumptions may or may not have been correct. These comparisons can be made by researchers working on projects where they can compare pre-project assumptions with post-project results.

IIMI as an independent agency is in an unique position to draw conclusions in an objective way. The results of such an analysis could be very useful in highlighting the requirements for improving the prospects for success of investments in irrigation. If a lack of knowledge about the resource base is as important a constraint as has been suggested, this indicates the obvious need for gathering more detailed information before moving ahead, and preparing and implementing projects. A simple conclusion of this nature can have far-reaching consequences.

5.4.4 Financial Constraints

One widely accepted opinion is that a shortage of finance for recurrent expenditures is a major constraint on the maintenance of irrigation works. It is often said that donors prefer funding capital components in projects and that local leaders prefer new projects to making funds available for maintaining existing projects. In many instances, too, capital budgets are separate from recurrent budgets, and the budget for recurrent expenditures receives far less attention than does the capital budget. One major challenge for irrigation research is to incorporate operation and maintenance costs into the economic analysis of the feasibility of projects from the outset.

If it can be demonstrated that the shortage of current expenditure is a major bottleneck, then this would have obvious implications for the financing of irrigation projects, and hopefully, for improving maintenance in the future. Any research into the problems of recurrent expenditures will involve examining how the recurrent expenditures are actually deployed. There are many possible explanations for poor maintenance, including poor construction of physical structures, that are not necessarily related to the availability of recurrent expenditures. Nonetheless, a hypothesis that should be examined is: the lack of finance to meet recurrent expenditures explains poor operation and maintenance.

A related important issue, which could well be a separate research topic, is whether there is any substitutability between technologies that involve a combination of capital-intensive investments that require limited current expenditures, and technologies that have low capital input but greater recurrent expenditures. If there is substitutability, then this would involve comparing the advantages of a high initial layout with low operational maintenance expenses, to a low initial payout with high operational maintenance expenses.

5.4.5 Water Contamination and the Intensification of Agricultural Production

Environmentalists are much concerned about the effects of intensification of production in irrigated areas. Intensification has led to substantial increases in the use of agro-chemicals, especially fertilizers and pesticides. There is concern that these inputs have contaminated water supplies by seeping into aquifers or draining into streams and rivers. Where this happens, the results may worsen the quality of water, with harmful consequences. These include negative effects on human health, as well as reducing the potential for increasing yields on irrigated land where poor-quality water is recycled with detrimental effects on output.

It is desirable to learn whether improved methods of irrigating land can limit environmental effects of intensification. This would involve examining the extent to which poor water use efficiency in irrigated areas is a major source of water quality problems. The assumption is that the use of water in excess of crop needs tends to result in greater surface runoff and waterlogging. Both can result in increased agricultural chemical contamination.

The hypotheses to be tested are that increased chemical discharges arise because the use of water in excess of crop needs tends to result in greater runoff and impeded drainage, with an increase in the discharge of chemicals such as nitrates. Where this happens, it becomes necessary to consider what management practices associated with irrigated farming can reduce water contamination. These practices might encompass the timing of irrigation, the amount of water applied, the uniformity of application, and the rate of application. This applies especially to wheat-rice rotations, and the stagnation in yields — if not actual declines — in major irrigated areas of Asia. Strategies to improve the efficiency of water use could include those that would apply in a more general context — pricing of water, attaching value to water through a process of education, better irrigation scheduling, introduction of techniques such as drip irrigation, plus some technical assistance for soil moisture testing. Since there is bound to be increasing use of agro-chemicals in the future to increase yields, it is important that managers have a better knowledge of how to cope with contamination problems, or rather, how to prevent or limit contamination problems more successfully than they have in the past.

IIMI should work with other centers in the CGIAR system on these problems.

5.4.6 Depletion of Groundwater Resources

A major concern is about the consequences of the rapid expansion of mechanical pumps and the impact on water resources. There are many questions raised by the spread of pumps, but two call for more information than is presently available. The first is the extent to which the spread of pumps is depleting groundwater and what this might entail. The second is the relationship between the continuous recycling of water through pumping and its effects on the quality of water and on plant yields (IIMI is working on this in Pakistan).

Both these issues involve inquiries of a technical nature. A better understanding of both issues is essential if steps are to be taken to insure sustainable development. To guard against degradation of the aquifer and degradation of water quality, it is necessary to establish the limits of sustainable water yield of the aquifer and monitor extractions accordingly. The monitoring should be done by means of appropriately spaced observation wells. Evaluation of sustainable water yields must be done by means of regional water balance studies, seepage measurements, and determination of aquifer hydraulic properties (storage capacity and transmissibility).

If it is found that the water table is falling rapidly, it may be necessary to introduce alternative mechanisms to ensure proper spacing of wells and to establish a monitoring system to ensure that any regulations are implemented. How should this be done in a least cost but equitable way? IIMI should be in a position to contribute to this debate.

5.4.7 Decentralized Management and Farmer Participation

The UNCED and a number of other international and national bodies have urged that greater efforts be made to encourage the development of local institutions to manage irrigation. The local institutions that do exist are both formal and informal, and include government-sponsored entities as well as nongovernment organizations. These institutions are organized around water users, farmers' groups, and other groups with common interests; they include groups operating at all levels in farmer-managed systems.

Many governments are seeking ways and means of reducing budgetary outlays, especially recurrent expenditures, for the operation and maintenance of irrigation systems. At the same time, there is increased awareness of the effective roles that some nongovernmental organizations have played in operating and maintaining components in public-sector irrigation systems, and in managing farmer-managed systems. Consequently, some governments have been interested in shifting the financial burdens and responsibility for managing systems to the private sector, and there have been moves to encourage nongovernmental organizations to take over management of systems.

There have already been "turnovers," notably in the Philippines. The sentiment to expand (both complete and partial) turnovers is growing. There appears to be much to be gained by learning from the experiences in the Philippines and other countries, especially in connection with large gravity systems that have been turned over. Water users of these systems have had to face the perennial problems that confront all nongovernmental organizations in "scaling up" the size of their operations. It would be useful to know more about how farmers have adjusted to the change in systems, and how the management has incorporated farmers' views in their decision-making process and whether these experiences are replicable elsewhere in Asia.

IIMI has already undertaken some highly regarded cooperative research on farmer-managed irrigation systems and the turnover process. It is strongly recommended that this work be continued, and if possible it should include work on the problems outlined above.

5.4.8 Diversification of Production

Rising incomes are leading to increasing demand for high unit value products, especially fruits and vegetables in the neighborhood of large urban centers. Farmers are responding to market opportunities. However, the layout of irrigation in many of these areas has been designed for rice production so that there are problems in adapting irrigation for different farming systems.

Action research could be very useful in helping managers to explore particular ways and means of introducing different regimes from those which have been in place for many years. There will be more difficulty in dealing with lowland rice than upland rice. Nevertheless it is important that there be a better grasp of what is involved now, or what might be involved in the future, if high unit value crops are to be substituted for rice production in areas where there are markets for these crops.

5.4.9 Gender Issues

In general there is very little information on gender issues as they relate to irrigated agriculture. A recent examination of 271 irrigation projects funded by the World Bank shows that gender issues were only mentioned in 10 of these projects or 3.7 percent of the total. Not one report contained a significant discussion on gender or a proposal for action, or mention of action that had been taken. A recent survey of completed irrigation projects revealed that the investment in Morocco's Doukkas Irrigation Project had greatly increased women's labour input and the women in question regarded this more as a burden than an opportunity [World Bank 1993].

There has been some concern expressed about the effects of irrigation on changes in water availability for household purposes. Since women are the primary providers of household services, this aspect of irrigation affects women differently from men. Intuitively it would seem that this factor should be given weight in the design of irrigation systems. As yet this subject has received little attention. Once again one reason for this may well be that so little is known about how irrigation affects lives of women.

IIMI has started a modest program to examine gender issues. This program is starting by gathering primary data through field surveys on the role of women in irrigated agriculture in a number of different social, economic and ethnographic environments. Once the data have been assembled and processed, it is expected that there will be a firm basis for assessing the significance of the gender factor and where and how it should be incorporated in the design and management of irrigation systems. Given the intense interest in issues of this kind among the world's development community, it is to be hoped that IIMI will have adequate resources to give sustained support to research of this nature.

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CHAPTER V

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Appendix

BIOTECHNOLOGY

David Hopper argues that without major agricultural productivity gains in the developing countries in the next 20 to 30 years "I do not see us being able to beat the Malthusian proposition." Expanded use of existing technologies and more effective management of water resources are not enough, he concludes. Only a technology with such immense potential as modern biotechnology, and particularly genetic engineering, can be expected to produce such gains [Hopper].

Basically, modern biotechnology provides a new set of tools for dealing with age-old problems; it brings a new dimension into agricultural research in terms of understanding cellular and molecular mechanisms. Biotechnology includes those technologies based on recombinant DNA technology, monoclonal antibodies, and new cell and tissue culture techniques, including bioprocessing techniques. A recent phenomenon, it was only in 1953 that Watson and Crick discovered the double helix structure of DNA, the molecule of heredity. Then, in 1960, the genetic code was deciphered, and in 1973, the first transfer of genetic material from one organism to another took place. Since then, most of the research has focused on human and animal health. Moreover, much of the work has been carried out by private companies with an eye to patentable products. As a result, research on plant genes and viruses, particularly outside the temperate zone, has received relatively little attention (a main exception to this is the Rockefeller Foundation Program supporting work on rice).

There is much speculation as to when agricultural biotechnology will begin to make an impact, but because the underlying variables are quite elusive, any such speculation should be viewed with extreme caution. Biotechnology, as Gabrielle Persley [1990] points out is, "a complex topic, meaning different things to different people, and encompassing science, business, and policy issues . . . it depends on advances in biology, genetics, chemistry, and engineering for its success." Nevertheless, Ms. Persley has attempted to provide a guide which may aid us in our speculation. By categorizing biotechnology, and its continuous and progressive nature, Ms. Persley has designed what she calls the "gradient" of biotechnologies. It describes the increasing basic scientific knowledge, complexity, financial support, and the estimated incremental time increases required to reach each level of technology. The list starts with those that are technically simpler and proceeds to those that are more complex. The discoveries made in the simpler technologies lead to the more complex ones, and usually the simpler are required for the success of the more complex ones. Emphasizing this continuity — one leads to the other which is often dependent on the former — the gradient is particularly useful when dealing with countries in various stages of scientific development. Programs and strategies must consider the best point of entry along the gradient, recognizing where the technology has come from, what is required for success, and where it may lead. Briefly, the gradient puts biological nitrogen fixation at the bottom left of the gradient (requiring a minimum of skill, time, and financial resources), while placing genetic engineering of animals and plants at the top right.

Using her gradient, Ms. Persley believes that modern biotechnology soon may lead to reduced crop losses from disease, and corresponding reductions in costs associated with agro-chemical use. Because the technology is scale-neutral, it may be of particular use in low-input agriculture, where the costs for such chemicals can be crippling to small farmers. Genetically engineered bio-control agents, for instance, may decrease the need for pesticides. Similarly, genetic engineering is expected to produce virus-resistant varieties of rice not much later than by the year 2000, while the development of fungi and viruses-resistant wheat may take only a few years more. Another early performer, of particular importance in regions with inherently poor soils (such as Africa), or degraded soils, will be the production of bacteria strains with the ability to fix nitrogen. Agricultural diagnostics, and genetic mapping, particularly for such traits as drought resistance and salinity tolerance, also hold promise, though exact time frames are hard to predict.

Biotechnology is said to promise early benefits for livestock, too, including new diagnostics, vaccines, and embryo technology. In forestry, advances in biotechnology could lead to the development of new bio-control agents against pests and disease.

The overall impact of biotechnology on crop production remains to be seen. Many knowledgeable scientists believe that molecular biologists and geneticists will make sufficient progress so that their work will have a profound impact on yields of basic crops in the future. This may be correct but there are also scientists who emphasize the many formidable obstacles to be overcome before there can be progress in increasing the biomass and yield capacity of the basic staples. There is only an elementary understanding of the "secret of what controls yields." Increasing yield capacity will involve the manipulation of many genes and as yet this remains well beyond the reach of molecular biologists and geneticists. Given the possibility that many crops will reach production plateaus in the next century, it is essential that every effort be made to make progress on this frontier of technology. Failing this the outlook beyond 2025 becomes increasingly bleak. In the interim though, modern biotechnology will generate a stream of products that will enhance yield stability at a lower cost than would be attained by using conventional methods.

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Personal observations of Peter Carlson, Chief Scientist at Crop Genetics International, Maryland, U.S.A. and Dr. Norman Borlaug, Nobel Laureate, CIMMYT, Mexico.