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The Role of Rainfed Agriculture in the Future of Global Food Production

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EXECUTIVE SUMMARY

This paper examines future prospects for rainfed cereal production, and its importance in the evolving global food system. The IMPACT-WATER integrated water-food modeling framework developed at IFPRI is applied to assess the current situation and plausible future options of irrigation water supply and food security, primarily on a global scale. This model simulates the relationships among water availability and demand, food supply and demand, international food prices, and trade at regional and global levels. Globally, 69 percent of all cereal area is rainfed, including 40 percent of rice, 66 percent of wheat, 82 percent of maize and 86 percent of other coarse grains. Worldwide, rainfed cereal yield is about 2.2 metric tons per hectare, which is about 65 percent of the irrigated yield (3.5 metric tons per hectare). Rainfed areas currently account for 58 percent of world cereal production.

The baseline projection from the IMPACT-WATER model—which incorporates our best estimates of the policy, investment, technological, and behavioral parameters driving the food and water sectors—shows that rainfed agriculture will continue to play a major role in cereal production, accounting for about one-half of the increase in cereal production between 1995 and 2021-25. The importance of rainfed cereal production is partly due to the dominance of rainfed agriculture in developed countries. More than 80 percent of cereal area in developed countries is rainfed, much of which is highly productive maize and wheat land such as that in the Midwestern United States and parts of Europe. The average rainfed cereal yield in developed countries was 3.2 metric tons per hectare in 1995, virtually as high as irrigated cereal yields in developing countries.

Rainfed cereal yields in developed countries are projected to grow to 3.9 metric tons per hectare by 2021-25.

Irrigation is relatively more important in cereal production in developing countries, with nearly 60 percent of future cereal production in developing countries coming from irrigated areas. However, rainfed agriculture remains important in developing countries as well. Rainfed yields in developing countries are projected to increase from 1.5 metric tons per hectare to 2.1 metric tons per hectare by 2021-25, and rainfed area in developing countries will account for 43 percent of total cereal area, and rainfed areas will account for 40 percent of growth in cereal production.

A number of alternative scenarios show that more rapid growth in rainfed yield and production could compensate for reduced investments in irrigation or reduced groundwater pumping to eliminate groundwater overdraft, but that achieving the required improvements in rainfed production would be a significant challenge. Thus, for example, a scenario that eliminates groundwater mining throughout the work would result in a decline in irrigated cereal production of 20.1 million metric tons in China, 18.4 million metric tons in India, 18 million metric tons in WANA, 1.6 million metric tons in developed countries, and 53.0 million metric tons in developing countries as a whole in 2021-25 relative to the baseline. These reductions can be offset by an increase in rainfed area and yield, but the required increase in yields would be very large. Compared to the baseline, average rainfed cereal yield would need to increase by 13 percent or 0.6 metric tons per hectare in China, 20 percent or 0.30 metric tons per hectare in India, and 0.3 metric tons per hectare in WANA; rainfed cereal area will increase by 0.6 million hectares in China, 0.8 million hectares in India, and 0.10 million hectares in WANA.

The paper also undertakes a critical synthesis of the literature to assess the potential of actually achieving such significant increases in rainfed cereal yields beyond the baseline projections. It is essential in most of the world that rainfed production increases come mainly from yield increases, not from further expansion in area. Many environmental problems can develop from further expansion of rainfed production into marginal areas. Biodiversity losses can develop from the clearing of areas to be used for agriculture. When these areas are cleared, many plants native to the area may be lost, and disease and pest problems may also develop due to changes in the ecosystem. Soil erosion is also often a significant problem in areas of agricultural expansion. Many of the marginal areas to which agriculture expands in the developing world include hillsides and arid areas, which make soil erosion a particular concern. Three primary ways to enhance rainfed cereal yields are examined, increasing effective rainfall use through improved water management, particularly water harvesting; increasing crop yields in rainfed areas through agricultural research; and reforming policies and increasing investments in rainfed areas.

WATER HARVESTING

Water harvesting involves concentrating and collecting the rainwater from a larger catchment area onto a smaller cultivated area. The runoff can either be diverted directly and spread on the fields or collected in some way to be used at a later time. Water harvesting techniques include external catchment systems, microcatchments, and rooftop runoff collection, the latter of which is used almost exclusively for non-agricultural purposes. External catchment water harvesting involves the collection of water from a large area that is a substantial distance from the area where crops are being grown. Types of external catchment systems include runoff farming, which involves collecting runoff from the hillsides into flat areas, and floodwater harvesting within a streambed using barriers to divert stream flow onto an adjacent area, thus increasing infiltration of water into the soil. Microcatchment water harvesting methods are those in which the catchment area and the cropped area are distinct but adjacent to each other. Some specific microcatchment techniques include contour or semi-circular bunds, and meskat-type systems in which the cropped area is immediately below the catchment area that has been stripped of vegetation to increase runoff.

While many water harvesting case studies and experiments have shown increases in yield and water use efficiency, it is not clear if the widespread use of these technologies is feasible. Construction and maintenance costs of water harvesting systems, particularly the labor costs, are very important in determining if a technique will be widely adopted at the individual farm level. The initial high labor costs of building the water harvesting structure often provide disincentives for adoption. The initial labor costs for construction generally occur in the dry season when labor is cheaper but also scarce due to worker migration; maintenance costs, on the other hand often occur in the rainy season when labor costs are higher due to competition with conventional agriculture. Thus, while many case studies of water harvesting methods show positive results, these methods have yet to be widely adopted by farmers. Some projects may require inputs that are too expensive for some farmers to supply. In addition, many farmers in arid or semi-arid areas do not have the manpower available to move large amounts of earth that is necessary in some of the larger water harvesting systems.

In addition to water harvesting, the use of improved farming techniques has been suggested to help conserve soil and make more effective use of rainfall. Conservation tillage measures such as minimum till and no till have been tested in some developing countries. Precision agriculture, which has been used in the United States, has also been suggested for use in developing countries. Along with research on integrated nutrient management, applied research to adapt conservation tillage technologies for use in unfavorable rainfed systems in developing countries could have a large positive impact on local food security and increased standards of living.

AGRICULTURAL RESEARCH TO IMPROVE RAINFED CEREAL YIELDS

A common perception is that rainfed areas did not benefit much from the Green Revolution, but breeding improvements have enabled modern varieties to spread to many rainfed areas. Over the past 10-15 years most of the area expansion through the use of modern varieties has occurred in rainfed areas, beginning first with wetter areas and proceeding gradually to more marginal areas. In the 1980s, modern varieties of the major cereals spread to an additional 20 million hectares in India, a figure comparable to adoption rates at the height of the Green Revolution (1966-75). Three quarters of the more recent adoption took place on rainfed land, and adoption rates for improved varieties of maize and wheat in rainfed environments are approaching those in irrigated areas.

Although adoption rates of modern varieties in rainfed areas are catching up with irrigated areas, the yield gains in rainfed areas remain lower. The high heterogeneity and erratic rainfall of rainfed environments make plant breeding a difficult task. Until recently, potential cereal yield increases appeared limited in the less favorable rainfed areas with poor soils and harsh environmental conditions. However, recent evidence shows dramatic increases in yield potential in even drought-prone and high temperature rainfed environments. For example, the yield potential for wheat in less favorable environments increased by more than 2.5 percent per year between 1979 and 1995, far higher than the rates of increase for irrigated areas. A change in breeding strategy to directly target rainfed areas, rather than relying on "spill-in" from breeding for irrigated areas was a key to this faster growth.

Both conventional and non-conventional breeding techniques are used to increase rainfed cereal yields. Three major breeding strategies include research to increase harvest index, to increase plant biomass, and to increase stress tolerance (particularly drought resistance). The first two methods increase yields by altering the plant architecture, while the third focuses on increasing the ability of plants to survive stressful environments. The first of these may have only limited potential for generating further yield growth due to physical limitations, but there is considerable potential from the latter two. For example the "New Rice for Africa", a hybrid between Asian and African species, was bred to fit the rainfed upland rice environment in West Africa. It produces over 50 percent more grain than current varieties when cultivated in traditional rainfed systems without fertilizer. In addition to higher yields, these varieties mature 30 to 50 days earlier than current varieties and are far more disease and drought tolerant than previous varieties.

If agricultural research investments can be sustained, the continued application of conventional breeding and the recent developments in non-conventional breeding offer considerable potential for improving cereal yield growth in rainfed environments. Cereal yield growth in farmers' fields will come both from incremental increases in the yield potential in rainfed and irrigated areas and from improved stress resistance in diverse environments, including improved drought tolerance (together with policy reform and investments to remove constraints to attaining yield potential, as discussed in the next section). The rate of growth in yields will be enhanced by extending research both downstream to farmers and upstream to the use of tools derived from biotechnology to assist conventional breeding, and, if concerns over risks can be solved, from the use of transgenic breeding.

Participatory plant breeding plays a key role for successful yield increases through genetic improvement in rainfed environments (particularly in dry and remote areas). Farmer participation in the very early stages of selection helps to fit the crop to a multitude of target environments and user preferences. Participatory plant breeding may be the only possible type of breeding for crops grown in remote regions; a high level of diversity is required within the same farm, or for minor crops that are neglected by formal breeding.

In order to assure effective breeding for high stress environments, the availability of diverse genes is essential. It is therefore essential that the tools of biotechnology, such as marker-assisted selection and cell and tissue culture techniques, be employed for crops in developing countries, even if these countries stop short of true transgenic breeding. To date, however, application of molecular biotechnology has been limited to a small number of traits of interest to commercial farmers, mainly developed by a few life science companies operating at a global level. Very few applications with direct benefits to poor consumers or to resource-poor farmers in developing countries have been introduced—although the New Rice for Africa described above may show the way for the future in using biotechnology tools to aid breeding for breakthroughs beneficial to production in developing countries. Much of the science and many tools and intermediate products of biotechnology are transferable to solve high priority problems in the tropics and subtropics, but it is generally agreed that the private sector will not invest sufficiently to make the needed adaptations in these regions. Consequently, national and international public sectors in the developing world will have to play a key role, much of it by accessing proprietary tools and products from the private sector. However, there has been little detailed analysis of the incentives and mechanisms by which such public-private partnerships can be realized.

POLICY REFORM AND INFRASTRUCTURE INVESTMENT IN RAINFED AREAS

Cereal yields can also be increased through improved policies and increased investment in areas with exploitable yield gaps (the difference between the genetic yield potential and actual farm yields). Such exploitable gaps may be relatively small in high intensity production areas such as most irrigated areas, where production equal to 70 percent or more of the yield gap is achieved. However, with yield potential growing significantly in rainfed environments (see above) exploitable yield gaps are considerably higher in rainfed areas, because remoteness, poor policies and a lack of investments have often isolated these regions from access to output and input markets, so farmers face depressed prices for their crops and high prices or lack of availability of inputs. Riskier soil and water conditions in less favorable areas also depress yields compared to their potential.

Emerging evidence shows that the right kinds of investments can boost agricultural productivity far more effectively than previously thought in many less-favored lands. Increased public investment in many less-favored areas may have the potential to generate competitive if not greater agricultural growth on the margin than comparable investments in many high-potential areas, and could have a greater impact on the poverty and environmental problems of the less-favored areas in which they are targeted. Although rainfed areas differ greatly from region to region based on the physical and climatic characteristics of the area, certain development strategies may commonly work in many rainfed areas. Key strategies include the improvement of technology and farming systems; ensuring equitable and secure access to natural resources; ensuring effective risk management; investment in rural infrastructure; providing a policy environment that does not discriminate against rainfed areas; and improving the coordination among farmers, NGOs, and public institutions.

CONCLUSIONS

Rainfed agriculture will maintain an important role in the growth of food production in the future. However, appropriate investments and policy reforms will be required to enhance the contribution of rainfed agriculture. Water harvesting has the potential in some regions to improve rainfed crop yields, and can provide farmers with improved water availability and increased soil fertility in some local and regional ecosystems, as well as environmental benefits through reduced soil erosion. However, despite localized successes, broader farmer acceptance of water harvesting techniques has been limited, due to the high costs of implementation and higher short-term risk due to the necessity of additional inputs, cash, and labor. Water harvesting initiatives frequently suffer from lack of hydrological data and insufficient attention during the planning stages to important social and economic considerations, and the absence of a long-term government strategy for ensuring the sustainability of interventions. Greater involvement of farmers from the planning stages and the use of farmers for maintenance and data collection and provision of appropriate educational and extension support could help expand the contribution of water harvesting.

The rate of investment in crop breeding targeted to rainfed environments is crucial to future cereal yield growth. Strong progress has been made in breeding for enhanced crop yields in rainfed areas, even in the more marginal rainfed environments. The continued application of conventional breeding and the recent developments in non-conventional breeding offer considerable potential for improving cereal yield growth in rainfed environments. Cereal yield growth in rainfed areas could be further improved by extending research both downstream to farmers and upstream to the use of tools derived from biotechnology to assist conventional breeding, and, if concerns over risks can be solved, from the use of transgenic breeding.

Crop research targeted to rainfed areas should be accompanied by increased investment in rural infrastructure and policies to close the gap between potential yields in rainfed areas and the actual yields achieved by farmers. Important policies include higher priority for rainfed areas in agricultural extension services and access to markets, credit, and input supplies. Successful development of rainfed areas is likely to be more complex than in high-potential irrigated areas because of their relative lack of access to infrastructure and markets, and their more difficult and variable agroclimatic

environments. Progress may also be slower than in the early green revolution because new approaches will need to be developed for specific environments and tried on a small scale before being disseminated more widely. Investment in rainfed areas, policy reform, and transfer of technology such as water harvesting will therefore require stronger partnerships between agricultural researchers and other agents of change, including local organizations, farmers, community leaders, NGOs, national policymakers and donors.

KEYWORDS: rainfed agriculture, water harvesting, crop breeding, agricultural policy, less favored areas.

TABLE OF CONTENTS

The Role of Rainfed Agriculture in the Future of Global Food Production

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INTRODUCTION

Eight hundred million people are food-insecure, and 166 million pre-school children are malnourished in the developing world. Producing enough food, and generating adequate income in the developing world to better feed the poor and reduce the number of those suffering will be a great challenge. This challenge is likely to intensify, with a global population that is projected to increase to 7.8 billion people in 2025, putting even greater pressure on world food security, especially in developing countries where more than 80 percent of the population increase is expected to occur. Irrigated agriculture has been an important contributor to the expansion of national and world food supplies since the 1960s, and is expected to play a major role in feeding the growing world population.

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However, irrigation accounts for about 72 percent of global and 90 percent of developing-country water withdrawals, and water availability for irrigation may have to be reduced in many regions in favor of rapidly increasing nonagricultural water uses in industry and households, as well as for environmental purposes. Out of concern over increasing water scarcity for irrigation, the role of water management and investments for irrigated agriculture and food security has received substantial attention in recent years (Hofwegen and Svendsen 2000; Rosegrant 1997).

However, rainfed areas currently account for 58 percent of world food production. Given the importance of rainfed cereal production, insufficient attention has been paid to the potential of production growth in rainfed areas to play a significant role in meeting future food demand. This paper examines future prospects for rainfed cereal production, and its importance in the evolving global food system. The paper starts with a critical synthesis of the literature on the prospects for increased rainfed crop production. The review of water management, agricultural research, policy reform, and infrastructure investment for rainfed agriculture is then utilized to develop a “business-as-usual” baseline scenario and a number of alternative scenarios for future growth in rainfed agriculture, explicitly linked to alternative outcomes for the driving forces behind rainfed growth. These scenarios are then implemented in the IMPACT-WATER holistic modeling framework, in order to assess their impact on future global food supply, demand, trade, and prices.

SOURCES OF GROWTH IN RAINFED CROP PRODUCTION

In order to increase production, farmers have two options, either to use extensive systems (which expand the area planted) or intensive systems (which increase inputs on a planted area in order to increase yields). In order to meet immediate food demands, farmers in many rainfed areas have expanded production into marginal lands. These fragile areas are susceptible to environmental degradation, particularly erosion, due to intensified farming, grazing and gathering. This problem may be especially severe in areas of Africa, in which the transfer from extensive to intensive systems was slower than in other regions (De Haen 1997).

Expansion of production into marginal areas can cause many environmental problems. When these areas are cleared, many plants native to the area may be lost, and disease and pest problems may also develop due to changes in the ecosystem. Soil erosion is also often a significant problem in areas of agricultural expansion. Many of the marginal areas to which agriculture expands in the developing world include hillsides and arid areas, which make soil erosion a particular concern.

These environmental impacts can lead to additional economic and health problems, particularly for the poor individuals that generally live in marginal areas. These impacts are generally greater on the poor than on other factions of the population due to the fact that they do not have adequate assets to mitigate the impacts of environmental degradation (Scherr 2000). Environmental problems can have far-reaching implications in poor communities through decreased agriculture production potential, which may further increase poverty, leading to increased malnutrition and poor health. Increasing production by expanding the planted area into marginal areas may have additional negative impacts on the population that moves into these areas, as living conditions can be much harsher than in more productive areas.

Because of these environmental consequences of area expansion, crop yield growth is a better solution than increasing the area planted in rainfed areas. McNeely and Scherr (2001) note that under some circumstances, increasing production on more productive lands—such as irrigated areas—can ease the pressure to use more marginal lands for cropland and help to keep those natural habitats from being destroyed. But as will be seen below, the potential for expansion of irrigated area is limited in most of the world. Therefore, intensive cropping systems that involve increased inputs such as labor, fertilizers, pesticides, or improved varieties to increase yields will be essential for rainfed crop production. Sustainable intensification of rainfed agriculture development can increase production while limiting environmental impacts. The three primary ways to enhance rainfed agricultural production through higher crop yields are: 1) to increase effective rainfall use through improved water management; 2) to increase crop yields in rainfed areas through agricultural research; and 3) to reform policies and increase investment in rainfed areas. These sources of growth are reviewed in turn.

WATER HARVESTING FOR RAINFED AGRICULTURE

Many developing countries located in arid or semi-arid regions experience significant problems in securing adequate amounts of water for rainfed crop production. Water scarcity problems in arid regions result simply from the lack of sufficient rainfall. Semi-arid regions, however, may receive enough annual rainfall to support crops but it is distributed so unevenly in time or space that rainfed agriculture is not viable (Reij, Mulder and Begemann 1988). Rockström and Falkenmark (2000) note that due to high rainfall variation in semi-arid regions, a decrease of one standard deviation from the mean annual rainfall often leads to the complete loss of the crop. Water loss through evaporation and runoff exacerbates water scarcity problems in these areas. Low rainfall areas that receive between 300 – 600 mm annually may be able to combat these problems using supplemental irrigation methods, but regions receiving less than 300 mm of annual rainfall must resort to other methods to secure enough water to support crop production (Oweis, Hatchum and Kijne 1999).

Water scarcity is a significant problem for farmers in Africa, Asia, and the Near East where 80 - 90 percent of water withdrawals are used for agriculture (FAO 2000). While farmers in some high-potential regions have been able to increase yields by 4 - 5 percent in recent years, farmers in the semi-arid tropics of Asia and Africa have only increased agricultural growth by less than 1 percent (Barghouti 2001). Farmers in these arid regions may be particularly hard hit, as development requires more water for domestic and industrial uses. Potential does exist, however, to increase agricultural water use efficiency through water harvesting and conservation techniques. Bruins, Evenari and Nessler (1986) estimate that an additional 3 - 5 percent of arid areas could be cultivated using runoff farming. Some water harvesting methods have proven successful in practice; trials of water harvesting in Burkina Faso, Kenya, Niger, Sudan and Tanzania have shown increased yields of 2 - 3 times those achieved in dryland farming (FAO 2000).

Water harvesting is a general term usually used to describe the collection and concentration of runoff for many purposes, including agriculture and domestic uses. Although specific water harvesting terminology varies by author, Reij, Mulder and Begemann (1988) list several characteristics that are generally involved in discussions of water harvesting. One characteristic is the importance of storage to many water harvesting systems due to the intermittent water flow in the arid and semi-arid areas where water harvesting takes place. In addition, most water harvesting operations consist of a catchment area and a receiving area for the capture of runoff, and are generally small both in size and in level of investment. Water harvesting activities occur near the location where the rain falls, therefore the storing of river water in large reservoirs and groundwater mining are generally not included under the category of water harvesting.

Water harvesting for agriculture (sometimes referred to as runoff farming) involves concentrating and collecting the rainwater from a larger catchment area onto a smaller cultivated area. The runoff can either be diverted directly and spread on the fields or collected in some way to be used at a later time. Different authors have classified water harvesting methods in various ways (see Reij, Mulder and Begemann (1988) for an extensive review of different classification methods) and a standardized classification system has yet to be developed. Pacey and Cullis (1986) classify rainwater harvesting techniques into three broad categories: external catchment systems, microcatchments, and rooftop runoff collection.

External catchment rainwater harvesting (sometimes referred to as macrocatchment water harvesting) involves the collection of water from a large area that is a substantial distance from the area where crops are being grown. Types of external catchment systems include runoff farming, which involves collecting sheet or rill runoff from the hillsides into flat areas, and floodwater harvesting within a streambed using barriers to divert stream flow onto an adjacent area, thus increasing infiltration of water into the soil. This type of water harvesting can be used for any number of different crops including row crops, trees or closely growing crops (Oweis, Hachum and Kijne 1999).

Microcatchment water harvesting methods are those in which the catchment area and the cropped area are distinct but adjacent to each other. Some specific microcatchment techniques include contour or semi-circular bunds made of earth, stone or trash, pitting, strip catchment tillage, and a meskat-type system in which the cropped area is immediately below the catchment area that has been stripped of vegetation to increase runoff. These methods are often used for medium water demanding crops such as maize, sorghum, millet and groundnuts (Habitu and Mahoo 1999).

Rooftop runoff collection involves the collection of runoff from slanted building roofs and is used almost exclusively for domestic consumption[5]. Some other water collection methods that have been used include fog collection and snow collection. Fog collection has been used in some mountainous coastal regions of Central and South America with large amounts of fog. This method utilizes fine nylon net strung between poles, which collects water droplets from condensed fog that is then stored for later use (Ringler, Rosegrant and Paisner 1999). This method generally does not result in large amounts of water being collected. Snow harvesting has also been used in some areas of Afghanistan (Pacey and Cullis 1986). In this method, snow is collected in the winter and stored in a deep watertight pit, which proceeds to slowly melt over the following summer. This method is not feasible in many arid and semi-arid areas that are located in warmer climates.

In situ water harvesting (or water conservation) methods are also used to help increase water use efficiency and are classified as water harvesting by some authors.

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[5] Rooftop runoff collection will not be discussed further in this paper given that it is generally not used for agricultural production.

These techniques will also be discussed in this section as they are often used in conjunction with water harvesting techniques, and as noted by Reij, Mulder and Begemann (1988), the distinction between water harvesting and *in situ* water conservation can be vague and hard to define. Many factors influence the usefulness of rainwater harvesting in general as well as the applicability of different methods in a particular area. Rainfall harvesting is only necessary in arid and semi-arid regions that receive low levels of rainfall or in which there is high intra or inter-seasonal rainfall variability that makes traditional rainfall agriculture infeasible. Rainfall intensity is one factor that impacts the effectiveness of the chosen water harvesting method. Li, Gong and Wei (2000) point out that while the bare ridge and furrow method has been shown to be quite effective in semi-arid areas of India where rainfall is generally high intensity, the same methods lead to water infiltration into the bare ridges and evaporation in areas of China that experience much lower intensity rainfall.

Other factors that influence the choice of rainwater harvesting method include topography, soil characteristics – particularly those related to water infiltration, and the choice of crop to be planted. Specific topographic characteristics that are necessary for rainwater harvesting include a landscape surface that facilitates runoff, and variations in altitude such that runoff flows down the slope and collects at a flat portion of the landscape. In addition, the cropped area soil must be deep enough and of a suitable texture to induce rainfall infiltration and retention (Bruins, Evenari and Nessler 1986). Loamy soils with a medium texture are generally the best-suited soils for water harvesting projects (Critchley and Siegert 1991). Due to the unique soil and landscape characteristics across regions, the same rainwater harvesting technique may produce quite dissimilar results in different areas. Particular attention needs to be given to the relationship between soil management and water availability to assure the best possible results from water harvesting operations.

Soil nutrient availability is essential in enhancing the effects of water harvesting and helping to ensure increased yields. Rockström (1993) addresses the importance of the water-nutrient equilibrium in crop production. He notes that although fertilizer application on fields with adequate moisture will increase yields, addition of nutrients during periods of drought may actually lead to decreases in yields. The relationship between soil nutrient levels and water harvesting is particularly important in areas of sub-Saharan Africa where soil nutrient levels are generally very low (Rockström and Falkenmark 2000). Tabor (1995) notes that regular application of animal manure is crucial to the success of microcatchment water harvesting in the Sahel as manure increases nutrient levels and improves the physical condition of the soil. Increased nutrient availability will also help to promote root development and canopy cover growth, which will increase water uptake by the crops and help to advance biomass growth (Rockström and Falkenmark 2000).

In addition to soil nutrient requirements, the physical structure of the soil also has an impact on the effectiveness of water harvesting. The degradation of the easily erodable soils in many arid and semi-arid regions leads to specific concerns regarding water harvesting methods. The erosion of the sandy surface of these soils, often due to the removal of vegetation by overgrazing or other means, exposes the clayey subsurface that forms a crusty layer with lower infiltration rates. While these crusted surfaces are often abandoned because of their low potential for agriculture, they may prove very useful for water harvesting by inducing runoff from the more impenetrable catchment area to the cultivated area below (Tabor 1995). The impact of raindrops on the eroded surface can also help to induce crusting (Abu-Awwad and Shatanawi 1997). In some situations, the runoff may also bring nutrient-rich litter along with it to the cultivated area, thus increasing the availability of nutrients to the crops (Nabhan 1984).

In cases when a crusty layer is not formed on the catchment area, the soil surface may be treated with other materials to reduce infiltration rates and promote runoff. Some chemical treatments have been used for this purpose, including asphalitic materials and paraffin wax. While these materials have increased runoff efficiency, they are generally only effective for 2-5 years (Ojasvi et al. 1999). Other materials such as plastic sheeting, fiberglass and concrete have also been used but these items are often too expensive for farmers in arid areas to afford.

Although the catchment area benefits from a layer of soil with low infiltration rates, this characteristic can be detrimental to crop production in the cultivated area. Very low infiltration rates that result from crusty surfaces can lead to waterlogging in the cultivated area, rendering the area unfit for crop production. The most appropriate type of soil for the cultivated area would be a deep fertile loamy soil. The presence of organic matter improves soil structure and allows for greater water infiltration and better penetration of plant roots. Deep soils are able to hold water from a water harvesting system and may also be able to provide a more nutrients for plant growth (Critchley and Siegert 1991).

WATER CONSERVATION

Water conservation methods, often referred to as *in situ* rainwater harvesting, include activities such as mulching, deep tillage, contour farming and ridging (Habitu and Mahoo 1999). The purpose behind these methods is to ensure that the rainwater is held long enough on the cropped area to ensure infiltration. These techniques are best suited to areas where rainfall and water holding capacity are sufficient to meet the crop water requirement but the amount of water infiltration is not adequate to reach the required moisture level (Habitu and Mahoo 1999). Some methods, such as mulching or the addition of organic matter, may also help to enhance the physical characteristics of the soil. Water conservation is often used in tandem with water harvesting techniques in order to achieve better results.

Deep tillage is a water conservation technique that improves soil moisture capacity by increasing soil porosity. In addition, runoff is reduced through increased roughness at the soil surface, which increases the time available for water to infiltrate the soil. This increased infiltration will increase the availability of water in the root zone to assist in plant growth. It is important to note, however, that these techniques are not suitable in all situations. Soil texture and structure as well as economic limitations that may exist if high capital inputs are needed. For example, draft animal power is essential to deep tillage due to the amount of power needed. In the Dodoma region of Tanzania, few areas use deep tillage techniques because the draft animal power is not available (Habitu and Mahoo 1999).

Contour farming is a technique in which tilling and weeding are done along the contours to help stop water runoff. Mulching or the addition of other organic material to the soil is a water conservation method that may both increase soil water availability by increasing soil water holding capacity and decreasing evaporation and improve the quality of the soil.

The addition of organic matter is often used along with other conservation methods to help increase water infiltration. When organic material is added with conservation tillage systems instead of using traditional mould-board ploughs, the decrease in erosion is even greater (Rockström and Falkenmark 2000). Fall and Faye (1999) note that animal traction used in place of tractors and heavy machinery decreases soil compaction, thus increasing soil aeration and water infiltration. These benefits are further increased when organic material is added to the soil. Beet (1990) found that in Ghana, a decrease in organic matter in soils from 5 percent to 3 percent decreased soil water retention from 57 percent to 37 percent. While animal traction may be useful in increasing soil aeration and infiltration of water, it may also result in soil degradation in the form of increased erosion (Fall and Faye 1999). The development of new farming techniques may be useful in combating these additional problems.

MICROCATCHMENTS

Microcatchment water harvesting systems consist of a distinct catchment area and cultivated area that are adjacent to each other (Habitu and Mahoo 1999). Boers and Ben-Asher (1982) additionally specify that the distance between the catchment area and the runoff receiving area of microcatchments must be less than 100 meters. Some advantages of microcatchments include the high specific runoff yield compared to larger catchments (Bruins, Evenari and Nessler 1986) and their simplicity, inexpensiveness and easy reproducibility (Boers and Ben-Asher 1982). Some authors suggest that microcatchment water harvesting systems offer significant increased cropping potential to smallholders without access to tractors in developing countries (Suleman et al. 1995). Microcatchments have been used in Asia, Africa, America and Australia.

Bunding and V-Shaped Catchments

Various forms of bunding and v-shaped microcatchments have been used successfully in some arid and semi-arid regions. Contour bunds are earth, stone or trash embankments placed along the contours of the hillside in order to trap rainwater behind them and allow for greater infiltration. Microcatchments using contour bunds were found to be successful for fruit tree plantations in Syria. At least twice yearly runoff was found to be sufficient for the selected tree species (almonds, pistachios, figs and grapes) used in the study. The same method was found to be uneconomical for mountainous areas as the construction costs were too expensive to offset any additional gains in yield (Oweis, Hachum and Kijne 1999). Semi-circular bunds are generally placed in a staggered formation and allow water to collect in the hoop for greater infiltration. Excess water is displaced around the edges of the bund when the hoop area is filled with water. Contour bunds are generally used on slopes less than five percent, while semicircular bunds are usually only used if the slope is less than three percent (Habitu and Mahoo 1999).

V-shaped microcatchments are similar to semicircular bunds except that a v-shaped catchment area is used instead of a hoop shaped area. A study conducted in Niger used v-shaped microcatchments in the production of millet and sorghum. The catchments were set up so that runoff would collect in the v-shaped area and then overflow around the sides once the basin was filled. The yields obtained from this study were greater than the national average yields for sorghum and millet in Niger. Due to these results, the author suggests that this type of microcatchment system should be pursued in areas where demand for agricultural land is high and/or the yields are below average (Tabor 1995).

Meskat-type Systems

Other types of microcatchments use a catchment area that diverts runoff water directly onto a cultivated area at the bottom of the slope. The meskat-type system differs from those previously described in that the field is divided into a distinct catchment area that is located directly above the cropped area instead of alternating catchment and cultivated areas (Habitu and Mahoo 1999). The cultivated basin is surrounded by a u-shaped bund in order to hold the runoff. Meskat-type systems are used for most types of cereal crops including maize, sorghum and millet (Habitu and Mahoo 1999). Suleman et al. (1995) conducted a study in the Northwest Frontier Province of Pakistan using water catchment aprons of various lengths and slope gradients to examine increases in soil moisture. In this method, a flat cultivated area is located in between two apron catchment areas. They found that soil moisture is significantly increased when aprons of 4 to 5 meters with 7 to 15 percent gradients are used. Moisture was increased by 59 percent in the first 15 cm of soil, by 63 percent in the second 15 cm, and by 80 percent in the 30 to 45 cm depth range. A study in Balochistan, Pakistan compared wheat yields for three experimental fields: a control area in which the entire area was planted, a water harvesting area with a ratio of 1:1 between the catchment area and cropped area, and a second water harvesting area with a ratio of 2:1 between the catchment area and cultivated area (Rees et al. 1991). While the water storage in the 1:1 and 2:1 trials increased by 55 and 43 percent respectively over the control, the yields were not always higher than the control. Averaged over the three years of the study, the 1:1 trial achieved yields that were 95 percent of the control yields. The 2:1 trial, however, obtained significantly lower yields than the control due to waterlogging problems.

Comparison of Microcatchment Techniques and Combination Methods

Kaushik and Lal (1998) conducted an experiment comparing five different water harvesting techniques (flat bed, bed and furrow, furrows on grade with eventual cultural operations, field bunding, and inter-row water harvesting) on rainy season crops in New Delhi, India. Significant differences in yield, moisture use, and moisture use efficiency were only found in lower rainfall year of the two-year study. The highest grain yield, monetary returns, soil moisture use, and moisture use efficiency were obtained using the bed and furrow method. Inter-row harvesting and bunding were found to have slightly better results than the two remaining methods. Kaushik and Gautam (1994) found increased pearl millet yields of 73.6 percent over the flat bed method when using a ridge and furrow seedbed, and an increase of 54.0 percent when using a flat seedbed with straw mulch. In the same study, the ridge and furrow method was shown to obtain a higher plant height, moisture use rate and water use efficiency compared to the flat bed method.

Another study in Jodhpur, India tested several water harvesting and moisture conservation methods on three tree species (Gupta 1995). The methods tested included a control, weeding only, weeding and soil working, weeding and 1 m diameter saucers, weeding and 1.5 m diameter saucers, weeding and 1.5 m diameter saucers with mulching, bunding microcatchments around each tree in a checkerboard design, and the ridge and furrow method. Increased height, collar circumference, crown diameter, and biomass accumulation over the control were found for all three tree species using the ridge and furrow method.

Some studies have used a microcatchment system along with a runoff enhancing or mulching technique in order to increase water use effectiveness. Li, Gong and Wei (2000) used a plastic-covered ridge to complement a ridge and furrow microcatchment system used in the low-intensity rainfall area of Gaolan County in China. Gravel mulch was also used in this study to hold water in contact with the soil for a longer period of time to increase infiltration and reduce evaporation. The test plots using plastic covered ridges obtained higher corn yields than the bare ridge plots. The highest yields were obtained from the plot with both plastic covered ridges and gravel mulched furrows, which produced yields 1.3 times greater than the plastic covered ridge only plot, 2.6 times greater than the bare ridge and furrow field, and 1.9 times greater than the bare flat soil control field.

Another study tested the use of various forms of waste (polyethylene bags, newspaper, stone, and marble) to line catchment areas in a shallow conical microcatchment agroforestry system in India (Ojasvi et al. 1999). These linings served to harvest water and mulch jujube trees. The largest plant height was obtained using linings of stone and marble. During the first year of the study, when the lining served only as mulch due to lack of rainfall, an increase of 33.3 percent and 25.0 percent in tree height over the control was found for stone and marble. Increases in tree height of 97.3 percent (stone) and 108.5 percent (marble) over the control were obtained in the second year when the linings served as mulch and aided in water harvesting. All types of lining were found to increase the soil moisture levels compared to the control.

EXTERNAL CATCHMENTS

External catchments or macrocatchment rainwater harvesting entails runoff collection from a large area located a significant distance from the cultivated area (Habitu and Mahoo 1999). The collected water is sometimes stored in a separate location before being used. Some types of external catchments include hillside sheet or rill runoff utilization, floodwater harvesting within a streambed, hillside conduit systems and ephemeral stream diversion.

Hillside Runoff and Conduit Systems

The hillside sheet or rill runoff system uses runoff from a hilltop or other areas, which then collects in flat areas where it is used for cultivation. The runoff is often used without any additional management (Habitu and Mahoo 1999). In some instances, bunding is also used in order to hold the runoff in the cultivated area. Maize, sugarcane and vegetables are often grown using hillside sheet or rill runoff systems. One of the predominant characteristics of external catchments is the low labor cost since there is generally no flood control management.

Hillside conduit systems are beneficial in areas where the runoff must travel over a long distance before reaching the cultivated area. When the slope along which the runoff must travel is very long, the velocity of the flow is often rather slow, which makes it quite possible that a significant amount of the water may be absorbed before it reaches the cultivated area (Bruins, Evenari and Nessler 1986). In this situation, it is useful to dig channels on the hillside, which increases the runoff flow velocity and allows more of the runoff to reach the field and be absorbed there.

Floodwater Harvesting and Stream Diversion

Floodwater harvesting within a streambed involves blocking the water flow, causing water to concentrate in the streambed. The streambed area where the water collects is then cultivated. It is important to make sure that the streambed area is flat with runoff producing slopes on the adjacent hillsides and that the flood and growing seasons do not coincide (Reij, Mulder and Begemann 1988). A terraced *wadi* system is one type of floodwater harvesting, in which a series of low check-dams are constructed across a *wadi* or ephemeral stream and the *wadi* area is cultivated. Some important factors to consider when determining if this method is suitable for an area include the soil quality and depth in the *wadi* and the ratio of catchment area of the *wadi* and the size of the area to be cultivated in relation to the rainfall runoff (Bruins, Evenari and Nessler 1986). This method has been used in many areas including North Africa, Punjab, Mexico, Colorado and Niger (Bruins, Evenari and Nessler 1986).

Ephemeral stream diversion is another external catchment system that is often used to harvest rainwater. In this technique, the water in an ephemeral stream is diverted and applied to the cropped area using a series of weirs, channels, dams, or bunds. Habitu and Mahoo (1999) describe two main ephemeral stream diversion systems. The first method uses a weir to divert the stream water into a cultivated area close to the stream that has been divided into several open basins using some type of bunding. Once one basin has filled, the overflow discharges into an adjacent basin. The second method uses a weir and a system of channels to divert the water into a rectangular basin. This method can be used on fields that are further away from the stream source. Reij, Mulder and Begemann (1988) describe this type of system as a form of water spreading. Some of the greatest efforts in ephemeral stream diversion include the large Marib Dam complex in Yemen and the Purron Dam complex in Mexico (Bruins, Evenari and Nessler 1986). A three-year macrocatchment (using a diversion ridge along a delivery channel) on-farm study in Botswana resulted in increased sorghum yields during two of the three seasons (Carter and Miller 1991). Water harvesting was found to improve sorghum yields most during seasons with inadequate or poorly distributed rainfall. Additional gains were found when fertilizer was utilized with water harvesting; in the 1987/88 season, yields were 110 percent higher due to water harvesting and yields increased 20 percent due to the addition of phosphorous and manure.

COSTS AND BENEFITS OF WATER HARVESTING TECHNIQUES

While many water harvesting case studies have shown increases in yield and water use efficiency, it is not yet clear if the widespread use of these technologies is feasible. Construction and maintenance costs of water harvesting systems are very important in determining if a technique will be widely adopted at the individual farm level. Additionally, extension and educational support to farmers is crucial to assure that water harvesting methods are adopted and maintained.

Several factors that influence the cost of catchment construction include labor and maintenance costs, soil characteristics, and the size and shape of the catchment (Tabor 1995). While some authors discuss these costs in general or empirically determine the costs for a specific case study, few cost comparisons of different water harvesting methods have been conducted. Kunze (2000) presents several different techniques for measuring the costs of water harvesting systems and applies some of these techniques using empirical data from a case study in Burkina Faso. The data required for cost measurements is often quite extensive. It was found that field-level data provided better results than household data for the analyses discussed. Using an investment analysis procedure, the construction of permeable rock bunds for sorghum production in Burkina Faso were found to be profitable at the farm level (Kunze 2000).

A study in Balochistan, Pakistan determined the costs, gross benefits and net benefits of different size microcatchments used to grow wheat and barley on valley floors (Rodríguez et al. 1996). Over six seasons (four seasons for barley), 3 different methods were used: a control area in which the entire area was cropped, an area with a 1:1 ratio between catchment area and cropped area, and an area with a 2:1 ratio between the catchment area and cropped area. Results showed an increase of farmers' income of 23 percent for wheat in the 1:1 ratio plots, and a decrease in income variation of 19 percent. The income of barley farmers was different, however, with the control methodology producing the best results due to the lower barley prices. A prior study in the same area of Pakistan found similar net benefits for a 1:1 catchment/cultivated area ratio trial compared to the control. The net benefits of the 2:1 ratio trial were found to be significantly lower than the control due to waterlogging yield losses (Rees et al. 1991).

Reij, Mulder and Begemann (1988) review cost estimates of several water harvesting studies in Africa. One Kenyan study cited found costs of constructing a water spreading system in Turkana to be in the range of about US$ 625 - US$ 1015 per hectare (Hogg 1986). Another Turkana project involving the improvement of a sorghum garden estimated construction costs of around US$ 750 per hectare (Cullis 1987). Two contour ridging projects in Kenya found significantly lower costs. Critchley (1987) found costs of US$ 110 - 330 per hectare for a contour ridging project in Baringo, while MoALD (1984) found total costs of around US$ 190 per hectare for contour ridges. The costs of an agro-forestry project in Burkina Faso were found to be much higher in the initial year than in later years. Wright (1985) found that in 1981, the initial year of the project, average costs per hectare were around US$ 1715, while average costs in 1985 and 1986 were around US$ 40 and US$ 20, respectively.

Labor and construction constitute the bulk of water harvesting costs in areas where ample land is available to construct the water harvesting structures. In land-scarce areas, the use of land for water harvesting will involve an opportunity cost, which may influence a farmer's decision to adopt water harvesting techniques. The initial high labor costs of building the water harvesting structure often provide disincentives for adoption (Tabor 1995). The initial labor costs for construction generally occur in the dry season when labor is cheaper but also scarce due to worker migration; maintenance costs, on the other hand often occur in the rainy season when labor costs are higher due to competition with conventional agriculture (Tabor 1995). While labor costs may be somewhat high in countries with less manpower (one study in the Negev desert found costs of US$ 10 - 40 per hectare cultivated), countries such as Pakistan with ample labor supplies are expected to be able to construct the systems for a much lower price (Suleman et al. 1995). The construction costs of small-scale water harvesting systems are quite small when compared to traditional large water projects – one estimate indicates that they are only 50-65 percent of the large-scale construction costs on a per unit cultivated area basis (Li et al. 2000).

Fertilizer costs are also important for establishing water harvesting systems. Due to the link between soil nutrients and water requirements, availability of soil nutrients is essential to the initial development of crops. Animal manure is probably the best option for most farmers in arid and semi-arid areas due to the high cost and lack of access to chemical fertilizer. Tabor (1995) suggests that livestock-owning farmers use water harvesting systems or in areas where animal manure is plentiful to help assure that the soil nutrient requirements are met.

SOCIO-ECONOMIC AND ENVIRONMENTAL ISSUES

While many case studies of water harvesting methods show positive results, these methods have still yet to be widely adopted by farmers. Many authors have pointed out the importance of considering the socioeconomic status of the farmers in the area where a technique is being employed (Bruins, Evenari and Nessler 1986; Oweis, Hachum and Kijne 1999; Tabor 1995; Critchley and Siegert 1991). Some projects may require inputs that are too expensive for some farmers to supply. In addition, many farmers in arid or semi-arid areas do not have the manpower available to move large amounts of earth that is necessary in some of the larger water harvesting systems. Another consideration that may be important is the traditional farming practices used in the area. For example, a project that requires animal tillage would not be attractive to farmers that generally plow by hand.

Considerations of risk may be very important in the initial decision of whether to adopt rainwater harvesting at an individual farm level. Especially due to the low economic status of many of the farmers in regions where rainwater harvesting is suggested, it is important that the expected returns from the adoption of the new technique be greater than the costs of implementing it.

Although many rainwater harvesting techniques work well at the experimental level, ensuring on-farm adoption proves to be an additional challenge in testing the techniques on a broader scale. Collective action issues may prove to be a problem when trying to implement water harvesting techniques. Since many of the water harvesting structures are large and require a substantial amount of land and labor to implement, the creation of these structures is often undertaken at a communal level. Problems develop at this level, however, as farmers are often not willing to supply voluntary labor to build the structures and the maintenance of communal water harvesting systems is often neglected. Reij, Mulder and Begemann (1990) note that very few water harvesting projects have made an effort to incorporate technologies that can be easily implemented at a family farm level.

Some authors point out particular considerations that are important when trying to assure widespread on-farm adoption. Factors that may ensure the acceptance of techniques at the farm level include the involvement of farmers from the planning stages and the use of farmers for maintenance and data collection which can create a sense of ownership over the project (Oweis, Hachum and Kijne 1999). In addition, it is useful to provide information about benefits of the water harvesting technology early on in the adoption process to help promote adoption through the provision of appropriate educational and extension support to ensure that the farmers have the knowledge necessary to implement the chosen technology (Critchley and Siegert 1991).

The environmental effects of water harvesting for agriculture should also be considered when determining whether to adopt a certain technology. Some examples of environmental damage that may occur due to water harvesting include salinization, sodification, low water tables or water logging, and soil degradation (Oweis, Hachum and Kijne 1999). An additional consideration is how the use of additional rainwater from rainwater harvesting techniques will affect water users downstream that may rely on the same water supply for their crop production.

MODERN FARMING METHODS

In addition to the water harvesting and conservation methods discussed above, the use of more modern farming techniques has been suggested to help conserve soil and make more effective use of rainfall. Conservation tillage measures such as minimum till and no till have been tested in some developing countries to conserve soil water and decrease the rate of soil water evaporation. Precision agriculture, which has been used in the United States, has also been suggested for use in developing countries. Along with research on integrated nutrient management, applied research to adapt conservation tillage technologies for use in unfavorable rainfed systems in developing countries could have a large positive impact on local food security and increased standards of living.

Conservation and no-tillage techniques may be especially helpful in areas where farmers do not have the capital or labor required for other techniques. The usefulness of these methods will also depend, however on the soil texture and structure. Trials of some conservation tillage techniques have been undertaken in areas of Sub-Saharan Africa with mixed results. Fall and Faye (1999) discuss the use of three seedbed preparation techniques (tillage in dry soil conditions, scarification and different sizes of sweeps, and direct seeding with no tillage) in dry soil for better soil-water management. Tillage in dry soil conditions is not sustainable over time and should not be recommended to farmers, as it can promote erosion from wind and first rain events. Scarification of the soil surface allows for protection against erosion and runoff due to the addition of crop residues to the soil. This method is used in the semi-arid region of the Sahel but specific results on yield increases have yet to be proven. Direct seeding in dry soil has been used in groundnut production in Senegal. Advantages to this method include: reduced production costs, diminished soil erosion, decreased runoff, less soil compaction, and better timeliness in seeding (Fall and Faye 1999). Smallholders in Namibia have also adopted dry seeding, planting on ridges, and minimum and no tillage, although some of the farmers do not seem to be aware of the soil and water conservation properties of these techniques as the methods were passed down from previous generations (Misika and Mwenya 1999). The commercial farming sector in Namibia has experienced even greater success than the small–scale farmers, having practiced conservation tillage methods for over 15 years (Misika and Mwenya 1999). Increased maize yields from 1.8 to 4.8 tons per hectare were found when breaking up the plough-pan in Tanzanian trials (FAO 2000).

No-tillage technology (often used with mulching) has been found to improve soil moisture conservation and thus reduce crop failure in dry years, particularly in arid or semi-arid areas such as Sub-Saharan Africa. Additional soil improvements such as enhanced soil structure and increased organic matter content have also resulted. Ekboir, Boa and Dankyi (2001) found that farmers in Ghana using no-till with mulch were able to reduce cash and labor investments and also experienced greater yields. However, despite the apparent benefits of conservation tillage, the use of mulch, and related technologies for rainfed agriculture, there has been very little farm level adoption of these technologies. In many instances the technology is very location specific and requires high levels of investments for tailoring it to specific conditions and to disseminate it to particular groups of farmers.

Precision agriculture has had some success in the United States and other developed countries. While traditional agricultural techniques have tended to apply the same management to an entire field, precision agriculture methods focus on information technology using site-specific soil, crop and other environmental data to determine specific inputs required for certain sections of a field. Many of these methods involve the use of technologies such as geographic information systems (GIS), satellites, and remote sensing. Precision agriculture can directly increase crop yields, and also improve water availability through greater relative infiltration of rainfall. In developing countries, the smaller farm sizes could allow for management on a field basis. Precision agriculture may hold significant promise in the future for agriculture in developing countries, as nutrient levels can vary greatly from field to field. For example, a recent study in the Philippines showed that variations in rice yields from 2400 to 6000 kg/hectare in 42 different fields were attributed to differences in soil nitrogen (Cassman 1999). More accurate analysis of soil nutrient levels could assist farmers in determining fertilizer levels specific to different areas in the field. However, a huge hurdle to overcome in implementing precision agriculture in developing countries is the availability of necessary data to determine these site-specific inputs, and the investment cost of obtaining and utilizing this data.

SUPPLEMENTAL IRRIGATION

Supplemental irrigation is another method used in low rainfall areas to assure that crops receive enough water in order to survive. While water harvesting is generally used in areas that receive between 100 – 300 mm of rainfall annually, supplemental irrigation is used in areas with a slightly greater annual rainfall of approximately 300 – 600 mm (Oweis, Hachum and Kijne 1999). Supplemental irrigation has been described as a technique used on crops that can be grown using rainfall alone, which applies a limited amount of water during times of low rainfall to ensure that enough water is received to support crop growth and stabilize yields (Oweis, Hachum and Kijne 1999; Perrier and Salinki 1987). The goal of supplemental irrigation is to provide enough water during critical growth stages to produce optimal yield per unit of water, not to provide stress-free conditions throughout the growing season with the aim of producing maximum yield (Oweis, Hachum and Kijne 1999).

This differs from conventional irrigation in that the amount of water applied in supplemental irrigation would not by itself be sufficient to ensure crop growth. Conversely, conventional irrigation supplies the entire water needs to the crop because rainwater may not provide sufficient water for plant growth for all or part of the season (Perrier and Salinki 1987). Conventional irrigation is used in regions where water is plentiful, while supplemental irrigation is often used in places where water is often scarce.

Timing of water application is one of the most important factors to be determined when using supplemental irrigation. Supplemental water applications are especially important when water is scarce during critical growth periods. Oweis, Hachum and Kijne

(1999) present a rule of thumb that for crops such as alfalfa, maize and spring grains, supplemental irrigation is needed when the soil water content drops to a rate of 50 percent of available water (which is equal to the field capacity minus the permanent wilting point) in the root zone. Other crops such as potatoes and vegetables will produce better when soil water is kept within the top 35 percent of available water.

The water used for supplemental irrigation can be obtained from a variety of sources. Groundwater, surface water, industrial wastewater, and water obtained through water harvesting methods are all used for supplemental irrigation. The water harvesting methods discussed earlier are often used in conjunction with supplemental irrigation since SI is often undertaken in low-rainfall areas. Important factors to consider when designing a water harvesting system for supplemental irrigation include the storage capacity, type of storage and storage location. Specific methods of irrigation used depend upon the resources available to the farmers in an area as well as any economic or labor costs that may be involved with setting up the SI system.

Potential benefits that can be achieved through the use of supplemental irrigation include increased yields, stabilization of yields across years, and creating conditions that allow for the use of higher technology inputs such as high-yielding varieties, herbicides and fertilizers (Oweis, Hachum and Kijne 1999). Research at the ICARDA research station in northern Syria has shown that water use efficiency can be greater under supplemental irrigation than under rainfed agriculture. Under research conditions, it was found that the application of a cubic meter of water at a time of water stress, combined with good management increased water use efficiency more than twice over that of rainfed production (Oweis 1999).

AGRICULTURAL RESEARCH FOR RAINFED CEREALS: RECENT TRENDS

A common perception is that rainfed areas did not benefit much from the Green Revolution, but breeding improvements have enabled modern varieties to spread to many rainfed areas. Over the past 10-15 years most of the area expansion through the use of modern varieties (MVs) has occurred in rainfed areas, beginning first with wetter areas and proceeding gradually to more marginal areas (Byerlee 1996). In the 1980s, modern varieties of the major cereals[6] spread to an additional 20 million hectares in India, a figure comparable to adoption rates at the height of the Green Revolution (1966-75). Three quarters of the more recent adoption took place on rainfed land, and adoption rates for improved varieties of maize and wheat in rainfed environments are approaching those in irrigated areas (Byerlee 1996).

The adoption rate of modern varieties of the major cereals varies by cereal type and region. Byerlee and Traxler (1995) show that in rainfed areas of developing countries, the spread of wheat MVs (Type I change[7]) lead to a 15-20 percent yield gain over traditional varieties (TVs), while annual yield gain attributed to adopting newer generations of MVs (Type II change) averaged 0.5-1.0 percent in high rainfall areas with almost no gains in very dry areas in the past thirty years. Compared to extensive diffusion in the United States where hybrid maize covered 96 percent of the maize area by 1960, a little less than half of the maize area in developing countries is sown to MVs (hybrids and open-

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[6] Wheat, rice, maize, sorghum and millet.

[7] Type I change occurs in areas where MVs are replacing traditional varieties (TVs), usually producing a sharp increase in productivity. Type II change occurs in areas where farmers are adopting newer generations of MVs to replace older generation MVs (Morris, Dubin, and Pokhrel,1994).

pollinated varieties[8]), ranging from 36 percent in sub-Saharan Africa (excluding South Africa) to 66 percent in East, South, and Southeast Asia (Pingali 2001). By the mid 1980s some 40 percent of rainfed lowland rice was planted to MVs (Byerlee 1994), an adoption rate much lower than the almost 100 percent adoption of MVs in irrigated environments of developed countries, but still significant. Adoption of MVs in upland rice ecosystems has been discouraged by the poor growing conditions and poverty levels (Crosson 1995), and there has been zero use of MVs in flood-prone environments (Byerlee 1994).

Improved varieties of secondary cereals and other grains such as pulses that are grown widely in marginal rainfed environments may also increase production. In Africa, sorghum and millet are grown in a harsh semi-arid tropical climate where inadequate rainfall and lack of irrigation make production of other cereal crops difficult to sustain. The adoption rate of improved varieties of sorghum in 1995/1996 ranged from zero to 50 percent in Southern Africa, with the extreme exception being the South African rate at 77 percent Maredia et al. (2000). The figure for millet was lower, ranging from zero in several countries to 25 percent, with Zambia showing the highest rate of 63 percent. Yields of sorghum and millet increased at an annual rate of 0.4 and 0.6 percent, respectively, from 1971 to 1996/1997.

The adoption of new varieties of sorghum and millet is likely to have a very small impact on yields unless there is also a fairly rapid increase of input use, especially inorganic fertilizers and quality seeds. However, with appropriate input use, improved millet varieties are estimated to increase yields by 22 percent or about 0.2-0.5 ton per

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[8] Open-pollination refers to pollination by wind, insects or other natural mechanisms (Zaid et al. 1999).

hectare even under the dry conditions of Sahelian countries like Niger (Mazzucato and Ly 1994).

FUTURE IMPROVEMENTS IN RAINFED CROP YIELDS: RESEARCH STRATEGIES AND POTENTIALS

This section reviews the potential for crop genetic improvements to enhance rainfed production. Significant long-term increases in potential crop yield are possible in favorable rainfed areas, but until recently, potential cereal yield increases appeared limited in the less favorable rainfed areas with poor soils and harsh environmental conditions (Byerlee et al. 1999). However, recent evidence shows dramatic increases in yield potential in even drought-prone and high temperature rainfed environments. Lantican and Pingali (2002) show that yield potential for wheat in these less favorable environments increased by more than 2.5 percent per year between 1979 and 1995, far higher than the rates of increase for irrigated areas. A change in breeding strategy to directly target rainfed areas, rather than relying on "spill-in" from breeding for irrigated areas was a key to this faster growth.

Similarly, in a comprehensive review of the evidence, Heisey, et al. (1998) show that well-adapted maize hybrids deliver significant performance benefits compared to open-pollinated varieties (OPVs) and local varieties even when grown in marginal production environments under low levels of management (see also Heisey and Smale, 1995; Bolaños, 1995; Cordova, Barreto, and Crossa, 1996; Edmeades, et al., 1997; Howard et al., 1999; De Meyer and Bänziger, 2000; Kirubi, et al., 2000). However, it is essential that hybrids be well adapted to local conditions. When hybrids have performed poorly compared to OPVs or local varieties, they have typically been introduced without having first undergone adequate testing to ensure their suitability for local production conditions or consumption requirements (Heisey, et al. 1998).

Past breeding strategies for both irrigated and rainfed areas emphasized yield maximization. For example, the maize seed presently distributed comes from varieties selected without sufficient attention to agronomic and socioeconomic factors that limit production: periods of drought and/or frost during the crop's vegetative stage, soil exhaustion, grain type and color, and forage qualities (Hibon et al. 1992). More recent crop genetic improvements through both conventional and non-conventional breeding have placed more of an emphasis on altering specific characteristics of the crop. Conventional breeding uses whole plants to select desired characteristics. These techniques have generally focused on maximizing yields through increased plant productivity and resistance to stress. Non-conventional breeding uses cellular and molecular biology techniques such as marker-assisted selection and cell and tissue culture techniques, which allow plants to be screened more quickly in the laboratory rather than the field. These techniques can also more rapidly and efficiently select for particular characteristics that may increase tolerance to diseases, pests, and adverse weather conditions, thus increasing yields. Non-conventional breeding also includes the transfer of genetic material from one species into another, creating transgenic or genetically modified organisms (GMOs) with beneficial characteristics that cannot be achieved through conventional breeding.

Both conventional and non-conventional breeding techniques are used with the goal of increasing yields. Three major strategies that are used to increase yields include an increased harvest index (HI)[9], an increase in the general plant biomass, and increased stress tolerance (particularly drought resistance). The first two methods increase yields by altering the plant architecture, while the third focuses on increasing the ability of plants to survive stressful environments. Each of these methods will be discussed and examples given in the subsequent sections.

INCREASING THE HARVEST INDEX

One method to improve yield is to increase the harvest index (HI), but this technique may have only limited potential for generating further yield growth (Cassman 1999; Evans 1998). In recently released varieties, the HI of rice is about 0.50-0.55, and the scope for continued increases is limited by the need to maintain sufficient leaf area and stem biomass for interception of solar radiation, physical support, and storage of assimilates and nitrogen used in grain filling (Cassman 1999). However, Khush (1996) suggests that it is possible to raise the HI of rice to around 0.60, and breeding for "super rice" with 200 to 250 grains per panicle rather than the 100 to 120 grains of modern high-yielding varieties is ongoing at the International Rice Research Institute (IRRI). However, IRRI estimates that it will not be available to farmers until 2005 at the earliest (IRRI 2000) and its adaptability to rainfed environments remains unclear.

Recent wheat cultivars appear to have a relatively low HI of 0.41-0.47 when grown with irrigation in California and Mexico but a further increase in HI might be feasible (Cassman 1999). Richards et al. (2000) list several traits used to improve the HI of wheat,

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[9] The harvest index is defined as "the ratio of grain to total crop biomass" (Cassman 1999).

of which tiller inhibition[10] and carbohydrate storage in stems and its remobilization to grain are of importance. The increased HI of maize has contributed little to the genetic yield gains of modern hybrids (Cassman 1999).

INCREASING TOTAL PLANT BIOMASS

Another strategy to increase yield is to increase the total dry matter (biomass per unit of land and inputs such as water and nitrogen) by increasing plant productivity. The development of hybrid varieties and increased photosynthesis are both techniques that focus on increased biomass.

Hybridization

Hybrid varieties increase plant productivity and provide greater yields than conventional varieties, making use of heterosis (or hybrid vigor), the phenomenon in which the progeny of two distinctly different parents grow faster, yield more, and resist stress better than either parent. Hybrid varieties of all of the major cereals have been developed throughout the past several decades. An overview of some of the major research results follows.

Hybrid maize was the first hybrid to be developed among the major cereals since it is a cross-pollinated species[11]. Attempts to introduce U.S. hybrids in subtropical and tropical environments during the 1950s failed due to the lack of adaptation to climate, disease, and insect pests (Dowswell et al. 1996). However, later improvements in hybrid maize have allowed diffusion of hybrid maize in subtropical and tropical regions. It is

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[10] Dryland cereal crops continue to produce an excessive number of tillers about half of which die at about the beginning of stem elongation.

[11] Cross-pollination refers to the fertilization of a plant from a plant with a different genetic make-up (Zaid et

estimated that nearly half of the maize area in developing countries is sown to hybrid maize, while improved open-pollinated varieties (OPVs) occupy a lower proportion of around 20 percent (Byerlee et al. 1999). The substantial adoption of hybrid maize in developing countries shows that the cost of purchasing hybrid seeds each planting season is not prohibitive for many farmers compared to the income benefits of these varieties.

The adoption of improved varieties has had a significant impact on maize production in Africa. For hybrids, most estimates suggest that on-farm yield gains have averaged at least 40 percent in favored areas, with dry areas or drought years providing at least a 30 percent yield gain. According to Morris, Clancy, and López-Pereia (1992), the yield gain due to improved OPVs is probably less, with a yield gain of about 15-25 percent compared to local materials in tropical areas. Applying these data to the estimated area planted to MVs in Africa, the overall yield gain due to adoption of MVs alone is 12-14 percent. Maize area expanded as well, especially in the drier savanna areas, since early maturing varieties and hybrids became available (Byerlee et al. 1994).

Although a male sterile/fertility restorer system[12] in wheat was discovered in the early 1960s, hybrid wheat has not been regarded as a viable option until recently (Jordaan 1996). Wheat is a self-pollinating plant like rice, requiring more complicated and costly processes to obtain male sterility than cross-pollinating plants such as maize. Cytoplasmic

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al., 1999).

[12] A male sterile/fertility restorer system is a process of hybridizing self-pollinating plants. By inducing male sterility in female line, the plants may be pollinated by the male line that contains a fertility restorer, so that fertilization occurs with cross-pollination. Male sterility origins are genetic, cytoplasmic, or cytoplasmicgenetic. The fertility restorer gene R, is dominant and is found in certain strains of the species, or may be transferred from a related species e.g., wheat. This gene restores male fertility in the male sterile line, hence it is known as restorer gene.

male sterility[13], nuclear male sterility and chemical hybridizing agents (CHAs), which are chemical agents used to produce male sterility, are three systems leading to male sterility in wheat. Due to the slow process of cytoplasmic male sterility that lacks versatility in methods of fertility restoration and the lack of cost-effective methods of maintaining nuclear male sterility, several companies abandoned their hybrid wheat research and development programs. Those who continued rescheduled their strategy to include CHAs and biotechnology (Jordaan 1996).

However, hybrid wheat varieties based on cytoplasmic male sterility/restorer systems have been developed, produced and marketed. In South Africa, wheat hybrids tested in 25 locations in the Free State in South Africa out-yielded the non-hybrids tested by 14.8 percent and 11.5 percent in 1994 and 1995, respectively[14]. These hybrids also have an advantage over conventional cultivars under conditions of water stress. Given these yield and water stress tolerance advantages, hybrid wheat technology may be of particular importance for wheat production under marginal conditions. CIMMYT (1998) suggests the problem with CHA toxicity in the past has been largely solved by a new generation of CHAs that are not only less toxic than previous versions, but in fact much less harmful than other chemicals utilized in agriculture.

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[13] Maternally inherited inability to produce functional pollen.

[14] Yield advantages are as much as 23.3 percent and 18.5 percent if the means of the highest yielding hybrids are used.

Although most hybrid rice has been bred for irrigated environments, the possibility of spreading the technology to rainfed areas may hold potential to increase rainfed yields. Since the release of the first commercial F_1 hybrid rice in 1976 in China, F_1 hybrid rice was planted on about 18 million hectares of the total 33 million hectares planted to rice by 1992. Those hybrid varieties yielded about 20 percent higher than inbred varieties (IRRI 1993). Hybrid rice technology has been limited to temperate and subtropical regions; however, tropical hybrids have recently become available in other Asian countries. Vietnam, India and Bangladesh plant hybrid rice on 200,000, 150,000, and 30,000 hectares respectively, reporting yield increases of up to 20 percent above the best yields of semi-dwarf rice varieties (IRRI 2001). Hybrid rice between *indica* subspecies increased yield potential by about 9 percent under tropical conditions. This gain is attributed to the greater biomass production rather than harvest index (Peng et al. 1999). The diffusion of hybrid rice has slowed in China because of the lower eating quality of grains. There has so far been limited success in developing high-yielding cultivars that also have better eating quality (Hossain 1996).

Further enhancement in yield potential may be possible from the use of intersubspecific heterosis[15] because the magnitude of heterosis is higher if the genetic difference in the parents is greater. *Indica* and *japonica* rice germplasm have, as opposed to the narrowed genetic diversity among the improved *indica* rice due to massive international exchange of germplasm, remained distinct, as there has been very little gene flow between these two varietal groups. As expected, the hybrids between *indica* and

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[15] Intersubspecific heterosis occurs when plants of different subspecies (such as the *indica* and *japonica* subspecies within the Asian rice species *Oryza sativa*) are crossed.

japonica parents showed higher heterosis for yield (Yuan et al. 1989). It has been shown that the level of heterosis in the *indica*/tropical *japonica* hybrids is higher than that of *indica*/*indica* hybrids (Khush 1996). In the medium term, yield increases of around 20 percent are possible through the adoption of hybrid rice (Virmani et al. 1994). The long-range prognosis is for a new plant type that could yield about 12.5-13 tons per hectare and, as a parent of the hybrids, increase this yield to 15 tons per hectare of grain (Khush 1995).

NERICA (New Rice for Africa), developed by crossing African and Asian rice species (*Oryza glaberrima and Oryza sativa*, respectively), is a recent breakthrough in intersubspecific hybrids (hybrids obtained by crossing 2 subspecies) that appears to have tremendous potential. NERICA varieties, bred to fit the rainfed upland rice environment in West Africa, produce over 50 percent more grain than current varieties when cultivated in traditional rainfed systems without fertilizer. In addition to higher yields, the NERICA varieties mature 30 to 50 days earlier than current varieties and are far more disease and drought tolerant than previous varieties (WARDA 2000).

Crossing African and Asian rice species has been difficult due to large genetic differences, but has been realized by a technique called embryo-rescue, which enables crosses between two varieties to survive and grow to maturity. Germplasm held in gene banks that hold seeds of 1,500 African rice varieties was one of the keys to success. Research shows that 10 percent adoption was achieved in three countries (Guinea, Côte d'Ivoire, and Sierra Leone). NERICA varieties may also be developed for use on rainfed uplands in Asia and Latin America (WARDA 2001). Between 2000 and 2004, breeders expect to release 37 new hybrids across West Africa. By 2005, they hope the new varieties will cover most of the rainfed upland rice land in West Africa. In addition to the upland areas, 31 new varieties are to be released in the rainfed lowlands (WARDA 2000).

Increased Photosynthesis

Increased photosynthesis or radiation use efficiency aims to improve carbon accumulation productivity, contributing to greater biomass production. One example of an attempt to increase photosynthesis is research to create C_4 rice plants. Tropical species such as maize, sorghum, and sugarcane are C_4 plants, which have evolved a more efficient photosynthesis mechanism than C_3 plants such as rice, barley, and wheat. C_3 plants may lose up to 50 percent of their recently fixed carbon through photorespiration, while the carbon loss of C_4 plants is greatly reduced or completely inhibited; therefore, C4 plants are more advantageous in their photosynthetic productivity. It should be noted, however, that C_4 species do not always have higher water use efficiency. Under non-ideal conditions such as drought, there are more tolerant C_3 species such as cowpea and cotton than the comparatively sensitive C_4 maize and sorghum cultivars (Ong et al. 1996).

The potential benefits from modifying rice, a C_3 plant, by incorporating traits currently found in C_4 plants such as maize, sorghum and sugar cane, are large. While the rice plant already contains all of the genes responsible for C_4 photosynthesis, they are not switched on and regulated as they are in maize. By transferring genes with an improved mechanism for the process of photosynthesis from maize to rice, researchers in the United States (Washington State University) and Japan (Tsukuba) have produced initial results that suggest that rice yields could be increased by up to 20 percent (FAO 2000; Ku et al. 2000).

BREEDING FOR THE TARGET ENVIRONMENT BY INCREASING STRESS TOLERANCE

Recent research has focused on bringing about yield increases that will last over a wide range of environments, providing food security and using genetic diversity in plant breeding instead of the prior approach of focusing only on increased yields through changes in plant architecture. This can be observed in the CIMMYT/ICARDA wheat program, in which about 35 percent of the bread wheat crossing program is devoted to abiotic stress tolerance (i.e. heat, drought, or cold) and about 44 percent towards pests and diseases. Varieties are selected under multi-location testing that represent wider range of biotic and abiotic stresses (ICARDA 1997).

Genotype by environment (G×E) interaction is influential in limiting breeding program efficiency (Ceccarelli et al. 2000). Two strategies to address G×E interactions include: 1) avoidance by selecting cultivars that are adapted to the complete range of target environments, or 2) exploitation through the selection of several different cultivars, each of which are specially adapted to a subset of target environments. Selection for specific adaptation is especially significant in breeding crops for unfavorable conditions, because unfavorable environments tend to be more heterogeneous than favorable environments (Ceccarelli et al. 2000). Successful breeding with consideration of environmental adaptability includes Sooty-Rascon, a new variety of durum wheat bred by CIMMYT for drought-prone environments in WANA regions. This variety produced at least 3.4 tons per hectare regardless of drought severity (CIMMYT 2000).

Drought Resistance

Breeding for drought resistance has a substantial positive impact on rainfed cereal yield, as moisture stress is the most pronounced constraint throughout rainfed environments. The trade-off between yield and stress tolerance has been a difficult task for plant breeding. For example, a crop variety with a short growing season may mature before drought occurs, but in rainy years its yields are likely to be less than that of a long-season variety. This complexity has slowed the development of drought-resistant crop varieties (OTA commissioned paper 1983). However, early maturing varieties may compensate for the yield loss by enabling double cropping. For instance, in the Bihar plateau in India, a switch to short duration varieties (85-105 days) from medium duration local varieties (120-130 days) in the medium and uplands helped the plants escape periodic drought during the rainy season and helped increase cropping intensity, as they fit well in sequential or mixed/intercropping patterns (Bagchi et al. 1995).

Drought tolerance improvement is probably one of the most difficult tasks for cereal breeders. This difficulty stems from the diversity and unpredictability of in-field drought conditions, as well as from the diversity of drought tolerance strategies developed by plants, which may be targeted and used as selection criteria. However, substantial progress has been made in recent years related to the physiology, genetics and molecular biology of drought tolerance in different plant species. Functional genomics increases understanding of drought tolerance control and defines strategies for crop improvement.

In several cereal species, genetic maps have helped to identify chromosomal regions controlling some traits related to drought stress response. Cereal crops such as maize, sorghum, rice, wheat and barley have been studied to identify regions controlling characteristics such as phenology, root characteristics, plant architecture and growth, photosynthesis, chlorophyll amount or "stay green" character, and water-use efficiency (This et al. 2000).

The limiting factors in rainfed wheat production are drought, temperature extremes, low nitrogen, low phosphorus, soil acidity, high aluminum saturation, and micronutrient deficiencies or excesses, making farm-level yields and aggregate production low and unstable (CIMMYT March 1999b). While half the area sown to wheat in developing countries and up to 70 percent of that grown in developed countries suffers from periodic drought (Trethowan and Pfeiffer 2000), wheat has been found to be relatively drought hardy, unlike maize, which may fail completely if the flowering stage is delayed beyond a critical threshold due to drought (Bolaños and Edmeades 1993). Breeding for drought tolerance in wheat, therefore, should focus more on improving overall radiation use efficiency under stress rather than reproductive stages of growth and partitioning (Reynolds et al. 2000).

In an Australian study, improved early vigor[16] in wheat was also found to be an important trait for increasing water-use efficiency and thereby grain yields in rainfed environments, but only at a medium rainfall site. At drier sites, greater early vigor initiates terminal drought earlier to reduce yield (Botwright et al. 2001). A collaborative effort between CSIRO of Australia and CIMMYT of Mexico combines a physiological understanding of growth with molecular genetics and conventional plant breeding to improve wheat yields in dry environments. A new wheat variety is about to be released

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[16] Early vigor refers to high leaf area index during early growth reducing evaporative water loss from the soil surface.

which has improved water efficiency bred by selecting for carbon isotope discrimination[17]. This wheat line combines highly desirable grain quality characteristics with excellent disease resistance as well as high water use efficiency. Grain yields are 10 percent higher than conventional varieties in dry environments. A genetic increase of 20 percent is considered feasible and at least a 20 percent gain is also achieved by improving agronomic practices such as timelier sowing, stubble retention systems, and fertilizer management. The release of this variety was initially limited to Australia (Richards et al. 2000).

Compared to wheat and rice, maize is more likely to be grown in areas that are regarded as marginal (Heisey and Edmeades 1999), even though maize possesses particular sensitivity to drought stress at anthesis, or flowering. Drought is thought to cause maize grain losses of up to 20 million tons annually in the tropics. Recurrent selection for improved drought tolerance has resulted in tropical maize yield gains during midseason drought of 5 percent. Ribaut et al. (1999) have shown that new breeding schemes involving optimal combinations of marker-assisted selection and conventional selection to improve drought tolerance in maize hold considerable promise for the future. Selection for traits correlated with drought yields has been shown to significantly improve the performance of maize under dry conditions at flowering, with no yield cost under well-watered conditions (CIMMYT 1998).

Maize breeding strategies in drought-prone environments include drought-tolerant varieties and early maturing varieties that escape drought. The R200 series of hybrids in Zimbabwe and the Katumani Composite-derived varieties in Kenya are examples of successful maize breeding for dry environments through the introduction of early maturing

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[17] This is the first cultivar that has been bred using the isotope discrimination technique.

varieties (Heisey and Edmeades 1999). New OPVs released in South Africa in May 2001, can have 30-50 percent higher yields than traditional varieties (World Bank 2001).

IRRI is developing modern high-yielding varieties of rice for rainfed lowlands that enhance seedling vigor and are better able to withstand submergence, drought, sodium, iron, and aluminum toxicity, phosphorus and zinc deficiency, pests, and diseases. Beginning in 1995 with 31 rice varieties, the team currently works with 10 reference lines. Over the next 3 to 5 years, the reference lines will be grown in the widest possible variety of environments, and their reactions carefully measured (IRRI 2001).

In late 2000, IRRI launched a working group on "aerobic rice," a high-yielding tropical rice plant that grows on dry but irrigated aerobic soil instead of in flooded paddies, and responds to irrigation and fertilization. The aerobic rice varieties developed to suit the subtropical and temperate climates are already being grown experimentally in China and the Philippines, and will soon be grown in India to test adaptability to the tropics. Conventional varieties already exist that grow in dry upland fields but they cannot match the yield potential of conventional commercial varieties, nor do they respond to irrigation or fertilization. Weed growth that is normally suppressed by flooding but can be dominant on dry land is another challenge for aerobic rice. The biggest concern with the current varieties of aerobic rice is a "yield collapse," in which the harvest is acceptable in the first season but drops by about 20 percent in the second and may fall a further 70 percent in the third. Although the reason for this yield-collapse is unknown, experience shows that it doesn't occur when rice is rotated with other crops. Aerobic rice is grown commercially while rotating with other crops under irrigation on 250,000 hectares in Brazil (IRRI 2001; Bouman 2001).

The spring barley variety “Mamluk”, developed mainly for drought-resistance through cooperation between ICARDA and the Krasnodar Research Institute of Agriculture in Russia, marked an average yield increase of 15-18 percent over current varieties in rainfed systems; extra yield was found to rise to 22-25 percent in more favorable conditions following two years of testing in Armenia (ICARDA 1999). ICARDA developed an improved barley landrace variety “Arta,” which averaged about 70 percent greater on-farm yields than most local landraces. Other drought-tolerant barley and wheat cultivars have been selected and are being tested under stress conditions in a number of CWANA and SSA countries (ICARDA 1999).

Sorghum variety S35, a very drought-resistant cultivar, was developed at the ICRISAT breeding program in India and was released in Cameroon in 1986 and Chad in 1989. Today, S35 occupies about 33 percent of the total rainfed sorghum area in Cameroon and 27 percent in Chad. Compared to farmers' best traditional varieties across all study sites in Cameroon and Chad, S35 yields 27 percent more output (grain) and reduces unit production costs by 20 percent. These farm-level impacts are larger in Chad where yield gain is 51 percent higher and cost reduction is 33 percent higher. Estimated net present value of the benefits from S 35 research spillover in the African region was US$ 15 million in Chad (Yapi et al. 1999).

COMBINING DESIRABLE TRAITS

Combining desirable traits such as increased biomass production, stress tolerance, and quality traits such as cooking quality are becoming a common strategy of breeders. With attention placed on breed the plant to fit the particular environments and farmers’ preference, a high adoption rate can be expected. For instance, non-conventional hybrids, MH17 and MH18, made from a top-cross of Malawian hybrids and a CIMMYT population, released in Malawi in 1990, were popular because farmers valued their processing characteristics and their resilience under drought and poor soil fertility. The smallholders' cash constraint prohibited many of them from purchasing the new seeds needed to continue growing the hybrids (CIMMYT 1998).

A major constraint to hybrid use, especially to resource-poor farmers, is loss of hybrid vigor if the next generation seeds are kept and used for the following season, forcing farmers to purchase seeds each season. One goal of breeders is to develop maize and rice varieties that will reproduce through apomixis[18], so that the seeds of a hybrid with this trait can be retained from one year to the next. The ability to transfer apomixis capability to maize from its wild relative, *Tripsacum* (although it is admittedly difficult) represents an untapped genetic resource for abiotic and biotic stress resistance (Conway 1997; Hoisington et al. 1999). CIMMYT is currently researching how to enhance apomixis in maize. Apomixis could greatly simplify the production of hybrid seeds and make it possible for farmers to buy seed of improved varieties at a much lower price. Some researchers estimate that the introduction of apomictic maize could reduce seed costs by at least 25 percent (CIMMYT March 1999a).

Researchers in Hong Kong, China, and the United States are developing genetically-modified F_1 hybrid rice, or "super hybrid rice," which may yield as much as 15 tons per hectare. The breeding process involves increasing photosynthesis by inserting a

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[18] Vegetative propagation through seeds. The offspring of apomictic plants are perfect genetic replicas ("clones") of the mother plant.

maize gene into the hybrid rice (Ku et al. 2000). This GM F_1 hybrid rice is expected to be ready for trial in 2004, and may be available to Chinese farmers by 2008. In the United States, RiceTech released XL6, the first F_1 hybrid rice variety for highly mechanized farming in January 2000. More than 180 farmers in Arkansas and Missouri planted XL6 on about 11,000 acres in 2001. Across the region, XL6 yields were 20 percent higher than the best conventional varieties (RiceTech 2000).

PROSPECTS FOR THE FUTURE

If agricultural research investments can be sustained, the continued application of conventional breeding and the recent developments in non-conventional breeding offer considerable potential for improving cereal yield growth in rainfed environments. Cereal yield growth in farmers' fields will come both from incremental increases in the yield potential in rainfed and irrigated areas and from improved stress resistance in diverse environments, including improved drought tolerance (together with policy reform and investments to remove constraints to attaining yield potential, as discussed in the next section). The rate of growth in yields will be enhanced by extending research both downstream to farmers and upstream to the use of tools derived from biotechnology to assist conventional breeding, and, if concerns over risks can be solved, from the use of transgenic breeding.

Participatory plant breeding plays a key role for successful yield increases through genetic improvement in rainfed environments (particularly in dry and remote areas). Farmer participation in the very early stages of selection helps to fit the crop to a multitude of target environments and user preferences (Ceccarelli et al. 1996; Kornegay et al. 1996).

Ceccarelli et al. (1996) demonstrate that participatory plant breeding may be the only possible type of breeding for crops grown in remote regions, a high level of diversity is required within the same farm, or for minor crops that are neglected by formal breeding. The study also suggests that the breeder was more efficient in selecting higher yielding entries in a high rainfall area, while the farmers were more efficient in selecting under high stress conditions (Ceccarelli et al. 2000).

Moving upstream, with the progress in mapping cereal genomes, the similarities between cereal crops will facilitate the integration of cereal genetic information and contribute to the faster identification of desirable traits. In order to assure effective breeding for high stress environments, the availability of diverse genes is essential. It is therefore essential that the tools of biotechnology, such as marker-assisted selection and cell and tissue culture techniques, be employed for crops in developing countries, even if these countries stop short of true transgenic breeding.

To date, however, application of molecular biotechnology has been limited to a small number of traits of interest to commercial farmers, mainly developed by a few life science companies operating at a global level. Very few applications with direct benefits to poor consumers or to resource-poor farmers in developing countries have been introduced—although the New Rice for Africa (NERICA) may show the way for the future in using biotechnology tools to aid breeding for breakthroughs beneficial to production in developing countries. Much of the science and many tools and intermediate products of biotechnology are transferable to solve high priority problems in the tropics and subtropics, but it is generally agreed that the private sector will not invest sufficiently to make the needed adaptations in these regions. Consequently, national and international public sectors in the developing world will have to play a key role, much of it by accessing proprietary tools and products from the private sector. However, there has been little detailed analysis of the incentives and mechanisms by which such public-private partnerships can be realized (Byerlee and Fischer 2000).

Most developing countries have virtually no capacity in molecular biology research, although strong programs exist in countries such as China, India and Brazil. These programs present special challenges and opportunities for accessing the new technologies, based on facilitation of private investments, public-private partnerships, local capacity to design around proprietary technologies, working with CGIAR centers as intermediaries and partners, and regional collaboration (Byerlee and Fischer 2000).

Development of GMOs also has significant potential for improving stress tolerance and yields in rainfed (and irrigated) environments, if concerns over consumer and environmental safety can be overcome. However, although cell and tissue culture and other agricultural biotechnology research are underway in many developing countries, most transgenic crops are planted in the developed world for developed country markets. In 1999, North America accounted for 82 percent of genetically modified plantings, with the United States alone accounting for 72 percent. In Asia, only China has a significant area planted to GM crops. The first country in the world to approve commercialization of GM crops, China has authorized the environmental release of over 100 varieties, including insect resistant-cotton, virus-resistant tobacco, papayas, green peppers, and potatoes, and slow ripening tomatoes. India is undertaking major research, but has yet to approve the commercialization of GM varieties. Modest research efforts are ongoing in Thailand and the Philippines (Pinstrup-Andersen 2000).

If successfully tapped, biotechnology will make an extremely important contribution to future crop yield growth, particularly in difficult rainfed environments. The debate over genetically modified organisms may significantly delay current crop improvement efforts and move the release dates of many improved varieties further into the future. When biotechnology moves beyond the application of molecular biology to assist conventional breeding to the creation of transgenic crops, it may introduce risks associated with the release of genetically modified material into the environment. These risks could include genes ‘jumping’ from genetically modified plants to other plants through cross-pollination, rapid creation of new pest biotypes through adaptation to genetically modified plants, and allergic reactions to the consumption of genetically modified foods. These risks are not well understood and they provoke a great deal of anxiety among some segments of the public. National institutions must have the capacity to evaluate these risks, to adapt and regulate breeding and crop management strategies to minimize these risks, and to implement and rigorously enforce appropriate regulatory systems.

POLICY REFORM AND INFRASTRUCTURE INVESTMENT IN RAINFED AREAS

Cereal yields can also be increased through improved policies and increased investment in areas with exploitable yield gaps (the difference between the genetic yield potential and actual farm yields). Such exploitable gaps may be relatively small in high intensity production areas such as most irrigated areas, where production equal to 70 percent or more of the yield gap is achieved (Cassman 1999). However, with yield potential growing significantly in rainfed environments (see above) exploitable yield gaps are considerably higher in rainfed areas, because remoteness, poor policies and a lack of investments have often isolated these regions from access to output and input markets, so farmers face depressed prices for their crops and high prices or lack of availability of inputs. Riskier soil and water conditions in less favorable areas also depress yields compared to their potential.

Historically, agriculture investment in most developing countries has focused on irrigated and high-potential rainfed areas in order to increase food production. The strategy of focusing on irrigated and high-potential areas has been widely used with the idea that investments in these areas will trickle down to help reduce poverty in the less-favored areas (LFAs). Increased food production in the irrigated and high-potential rainfed areas is expected to lead to a reduction in food prices, thus helping to alleviate poverty in LFAs as well. Under the assumption that the potential for agricultural development is limited in many LFAs, policies that emphasize the development of non-farm sectors of the economy and migration out of these areas are often suggested as long-term solutions in LFAs. Although these strategies have worked in some areas, many LFAs have fallen even further behind due to the poor growing conditions, inadequate rainfall and lack of investment (Rosegrant and Hazell 2000). Despite some out-migration to more rapidly growing areas, population size continues to grow in many less favored areas and this growth has not been matched by increases in yields. The result is often worsening poverty and food-insecurity problems, as well as the widespread degradation of natural resources.

Many of the expected benefits arising from rapid agricultural growth in high-potential areas have been confirmed (Pinstrup-Andersen and Hazell 1985; Hazell and Ramasamy 1991; David and Otsuka 1994). Nevertheless, Hazell, Jagger, and Knox (2000) note that the rationale for neglecting less-favored areas is being increasingly challenged by: a) the failure of past patterns of agricultural growth to resolve growing poverty, food insecurity and environmental problems in many less-favored areas; b) increasing evidence of stagnating levels of productivity growth and worsening environmental problems in many high-potential areas (Pingali and Rosegrant 1994; Pingali, Hossain, and Gerpacio 1995); and c) emerging evidence that the right kinds of investments can increase agricultural productivity to much higher levels than previously thought in many less-favored lands. Increased public investment in many less-favored areas may have the potential to generate competitive if not greater agricultural growth on the margin than comparable investments in many high-potential areas, and could have a greater impact on the poverty and environmental problems of the less-favored areas in which they are targeted (Hazell, Jagger, and Knox 2000). If so, then additional investments in less-favored areas may actually give higher aggregate social returns to a nation than additional investments in high-potential areas.

Support for this proposition is provided in recent studies by Fan and Hazell (1999), Fan, Hazell, and Thorat (1998), Fan, Hazell and Haque (2000), and Fan, Zhang, and Zhang (2001), which show that returns to public investments in rainfed and other less favored areas in India and China are generally higher than in irrigated areas. A similar pattern emerges in terms of poverty impact. For all types of investments, additional spending in many of the rainfed areas raises far more poor people above the poverty line than does additional investment in irrigated areas. These studies support an increase in policy and investment attention to rainfed areas.

The development of an agricultural sector is important to the economy of LFAs. Since there are currently many people living in these areas, a sufficient food supply is important in the near term. These areas provide unique challenges in that they generally have poor soils, low rainfall, high climate variability, and poor infrastructure. As discussed in previous sections, these less-favored, low-rainfall areas generally do not benefit from the same strategies that are used in high-potential areas or areas in which irrigation is possible.

Although LFAs can differ greatly from region to region based on the physical and climatic characteristics of the area, certain development strategies may commonly work in many LFAs. Rosegrant and Hazell (2000) list seven general features of suitable development strategies for LFAs: 1) promotion of broad-based agricultural development; 2) improvement of technology and farming systems; 3) ensuring equitable and secure access to natural resources; 4) ensuring effective risk management; 5) investment in rural populations and infrastructure; 6) providing the appropriate policy environment; and 7) reinforcing public institutions.

Encouraging broad-based agricultural development is especially important in the LFAs of developing countries due to the large number of smallholder farms. These small and medium-sized farms should receive priority in agricultural research and extension and receive access to markets, credit, and input supplies. In addition to the encouragement of agricultural development at the farm level, investments in research and development specifically geared toward LFAs are also important. As discussed in the previous sections, the development of water management techniques and advancements in cropping methods geared specifically toward low-potential rainfed areas can lead to increased production in those areas. Water management at the catchment level, controlled soil erosion, soil moisture and fertility improvement, and the production of higher value crops that may fit well into a particular environment are all improved farming methods that may be beneficial in LFAs (Scherr and Hazell 1994).

Ensuring equitable and secure access to natural resources is often very important in LFAs as land distribution is often insecure, the rate of landlessness is generally high, and land leases many times are short and insecure. Land tenure and common property resource issues are crucial when considering access to natural resources in LFAs. Secure land tenure can encourage farmers to engage in sustainable farming practices that may help increase production in LFAs. The investments required for sustainable development of agricultural land and other land improvements may not seem worthwhile to many farmers if they are unsure of how long they will be able to harvest the land. This is also often the case with water harvesting; Nasr (1999) notes that individuals are unlikely to undertake the investment needed to build water harvesting structures on land that they do not formally own.

Common property resources on LFAs are also of concern to many poverty-stricken residents of these areas. The collective ownership of common property resources in these areas can be an effective way to reduce risk for individuals since the group as a whole shares risk. Common property resources are likely to be degraded, however, if there is no body in control of management of the resource. Collective action undertaken by the group of resource users is often the most effective way of managing common property resources. Collective action is generally more successful when the number of resource users is small, the individuals involved in the collective action effort have similar goals for resource use, and the benefits received from being part of the collective action effort are significant (Rosegrant and Hazell 2000).

The management of risk is also important in LFAs due to the tendency of these areas to receive especially high or low amounts of rainfall and to experience catastrophic climate events such as drought that may affect production levels. One way to help alleviate risk is the development of new crop varieties and techniques, such as those discussed earlier in this paper that help to avoid common consequences of drought or other climate events. For example, drought and pest tolerant crop varieties and the development of soil moisture conservation and water harvesting techniques can help farmers to deal with these situations. Correctly designed government programs, such as safety-net programs, insurance and credit, can also help farmers to deal with these events. Agricultural insurance is another method used, particularly in developed countries, to help farmers deal with risk. In general, traditional crop insurance programs have not worked very well, particularly for poorer farmers. Area-based crop insurance that is based on rainfall instead of yield may be more appropriate for farmers in LFAs. Area-based insurance programs are better able to reach poor and rural farmers, and rainfall based insurance is easier and cheaper to use than yield based insurance (Hazell 1992).

Rainfed areas are often poorly placed to compete in a liberalized economy because of their restricted access to markets and high transport and marketing costs. Public sector investment in the infrastructure of rainfed areas can also help to develop the agricultural sector of these areas. Development in the electricity, transportation and telecommunications sectors can help with the marketing of food products, which would in turn impact the agricultural sector. Additional market reforms including price and trade liberalization can help to send the correct market signals to farmers and hopefully lead to increased market opportunities in rainfed areas. Investments in rural infrastructure as discussed above are also important in order to ensure that these market reforms lead to the expected increase in market opportunities.

Finally, it is important that public agencies are able to deal with the unique problems of rainfed areas. Many extension and agricultural research agencies have traditionally focused on irrigated and high-potential areas. The top-down approach to management that is used in many of these agencies also generally does not work well in the less-favored rainfed areas. As mentioned in the previous sections, involving the farmers throughout the process of implementing water harvesting systems or the planting of new hybrid varieties can increase the rate of adoption. Rosegrant and Hazell (2000) suggest that a more participatory approach by these agencies with more accountability to the farmers may help in the development of less-favored rainfed areas.

RAINFED AND IRRIGATED AGRICULTURE IN 1995

Rainfed and irrigated crop area and yield in 1995 are assessed based on data from FAO (1999) and Cai and Rosegrant (1999)[19]. Table 1 shows rainfed and irrigated cereal area, yield, production, and fraction of rainfed area and production, in several countries and aggregated regions in 1995.

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[19] 1995 is the most recent year for which it was feasible to assemble adequate data.

Table 1: Rainfed and irrigated total cereal area, yield, production in 1995, and fraction of irrigated area of the total, fraction of the irrigated production of the total, in selected countries and regions

	Irrigated Area	Irrigated Yield	Irrigated Production	Rainfed Area	Rainfed Yield	Rainfed Production	Rainfed Area	Rainfed Production
	(million ha)	*(mt/ha)*	*(million mt)*	*(million ha)*	*(mt/ha)*	*(million mt)*	*Percent*	*Percent*
USA	8.2	7.04	57.8	54.7	4.82	263.4	86.9	82.0
15 European Countries	9.4	6.32	59.4	26.0	4.79	124.4	73.4	67.7
Japan	2.1	4.39	9.2	0.2	3.28	0.7	9.7	7.5
Australia	2.6	2.31	6.0	11.8	1.64	19.4	81.9	76.3
Other Developed	2.1	2.84	6.0	23.4	2.58	60.5	91.7	91.0
Eastern Europe	5.9	4.23	25.1	18.0	2.87	51.6	75.2	67.3
Cenasia	9.4	1.14	10.7	11.9	0.57	6.8	56.1	39.0
Rest Former USSR	11.4	1.93	22.1	58.0	1.53	88.4	83.5	80.0
Mexico	3.1	4.74	14.7	7.4	1.66	12.4	70.6	45.7
Brazil	1.2	2.94	3.5	18.6	2.16	40.1	93.9	91.9
Argentina	1.0	4.79	4.7	8.5	2.54	21.6	89.6	82.1
Colombia	0.3	3.39	1.0	1.0	1.83	1.9	77.1	64.5
Other Latin America	1.9	3.42	6.6	6.2	1.66	10.4	76.5	61.2
Latin America	7.5	4.07	30.6	41.8	2.07	86.4	84.7	73.8
Nigeria	1.3	2.84	3.7	16.6	0.90	14.9	92.8	80.2
N Sub-Saharan Africa	1.1	1.51	1.6	29.0	0.65	18.8	96.4	92.1
C&W Sub-Saharan Africa	0.2	2.00	0.4	9.6	0.91	8.7	98.0	95.8
S Sub-Saharan Africa	0.6	1.90	1.1	8.1	0.95	7.7	93.4	87.6
E Sub-Saharan Africa	0.1	2.06	0.3	6.5	1.42	9.2	98.0	97.1
Sub-Saharan Africa	2.0	1.71	3.4	53.2	0.83	44.3	96.4	93.0
Egypt	2.6	5.48	14.3	0.0	0.00	0.0	0.0	0.0
Turkey	0.3	4.83	57.8	13.7	1.96	263.4	98.2	95.7

Table 1 (continued)--Rainfed and irrigated total cereal area, yield, production in 1995, and fraction of irrigated area of the total, fraction of the irrigated production of the total, in selected countries and regions.

	Irrigated Area	Irrigated Yield	Irrigated Production	Rainfed Area	Rainfed Yield	Rainfed Production	Rainfed Area	Rainfed Production
	(million ha)	*(mt/ha)*	*(million mt)*	*(million ha)*	*(mt/ha)*	*(million mt)*	Percent	Percent
Other W Asia & N Africa	6.9	2.81	19.4	20.3	1.02	20.6	74.6	51.5
W Asia & N Africa	9.8	3.58	34.9	34.0	1.40	47.5	77.7	57.6
India	37.8	2.65	100.3	62.3	1.20	74.6	62.2	42.7
Pakistan	10.4	2.02	21.1	0.8	0.60	0.5	7.4	2.3
Bangladesh	5.8	2.85	16.5	1.9	1.35	2.6	24.9	13.5
Other S Asia	3.7	1.62	6.0	2.9	1.35	3.9	43.5	39.2
South Asia	57.7	2.49	143.8	67.9	1.20	81.5	54.1	36.2
Indonesia	9.1	3.44	31.4	5.6	1.70	9.6	38.1	23.3
Thailand	2.1	2.67	5.6	8.8	1.52	13.3	80.7	70.4
Malaysia	0.5	2.36	1.1	0.3	1.45	0.4	35.9	25.6
Philippines	2.6	2.18	5.7	3.9	1.49	5.9	60.1	50.8
Vietnam	3.8	3.16	11.9	3.6	1.68	6.0	48.8	33.5
Myanmar	0.9	2.74	2.5	5.3	1.87	10.0	85.3	79.8
Other SE Asia	0.2	2.02	0.3	2.2	1.22	2.7	92.9	88.8
Southeast Asia	19.2	3.05	58.5	29.8	1.61	47.9	60.8	45.0
China	62.4	4.23	263.6	26.2	3.59	94.0	29.6	26.3
S Korea	1.0	4.41	4.4	0.2	3.29	0.6	16.1	12.5
Other E Asia	1.1	2.71	3.1	0.6	1.57	1.0	36.2	24.8
East Asia	64.5	4.20	271.1	27.1	3.54	95.7	29.5	26.1
World Other	0.0	1.63	0.0	0.0	0.42	0.0	81.8	53.6
World	213.1	3.48	742.3	474.3	2.18	1033.3	69.0	58.2
Developed	41.8	4.44	185.6	192.1	3.17	608.3	82.1	76.6
Developing	171.3	3.25	556.7	282.2	1.51	425.0	62.2	43.3

Developing countries rely substantially more on irrigated agriculture than developed countries, with 38 percent of all cereal area irrigated, accounting for 59 percent of total cereal production. Conversely, only 18 percent of all cereal area is irrigated in the developed world, accounting for 23 percent of total cereal production. Rainfed cereal yield in the developed world is almost double the rainfed yield in the developing world, and only slightly lower than the irrigated yield in the developing world. As a result, rainfed cereal production in the developed world contributes 59 percent of global rainfed production, and 34 percent of total cereal production.

For some countries and regions with an arid or semi-arid climate, the fraction of rainfed crops is very low, for example, zero percent of the cereal area harvested in Egypt and 7.4 percent in Pakistan is rainfed. Since rice is the dominant crop in Japan and South Korea, rainfed cereal harvested area occupies only 10 percent and 16 percent, respectively, of the total area harvested. Other countries in which the fraction of rainfed harvested cereal area is below 50 percent include Bangladesh, China, Malaysia, Indonesia, and Vietnam. The fraction of rainfed cereal harvested area in Nigeria, all Sub-Saharan African countries, and some South American countries such as Argentina and Brazil is over 90 percent, while in Latin America as a whole the percentage is a slightly lower 85 percent. Although none of Egypt’s cereal area is rainfed, the WANA region as a whole has a much higher fraction of 78 percent.

Globally, 69 percent of cereal area planted is rainfed, including 40 percent of rice, 66 percent of wheat, 82 percent of maize, 86 percent of other grains, and 85 percent of soybeans. The global rainfed harvested area of rice, wheat, maize, other cereals, soybeans, potatoes, sweet potatoes, and cassava and other roots is 560 million hectares in 1995, with cereals representing 85 percent of this total. Worldwide rainfed cereal yield is about 2.2 metric tons per hectare, which is about 65 percent of the irrigated yield. Rainfed cereal production accounts for 58 percent of worldwide cereal production.

The global rice harvested area is 146 million hectares, of which approximately 87 million hectares is irrigated, and 59 million hectares are rainfed. There is very little rainfed rice planted in developed countries, while rainfed rice occupies approximately 42 percent, or 59 million hectares of the total rice area in developing countries. Developing countries are also responsible for almost the entire world production, with 97 percent of the total world rice yield coming from developing countries. Rainfed rice yield in developing countries is 1.4 tons per hectare or about 44 percent of the total irrigated rice yield in developing countries, this amounts to 24 percent of the developing country total, and 23 percent of world production.

Globally, 222 million hectares of wheat was harvested in 1995, 66 percent of which was rainfed, and the remaining 34 percent irrigated. About 83 percent of the area planted to wheat in developed countries was rainfed, while in developing countries slightly less than half of the total wheat area planted was rainfed. Rainfed wheat yields in developed and developing countries are approximately 2.5 tons per hectare and 1.2 tons per hectare, respectively, while the irrigated yields are slightly higher at 2.9 tons per hectare and 1.7 tons per hectare. Rainfed wheat production contributes 33 percent of the total yield in developing countries, 81 percent in developed countries, and 52 percent worldwide.

Maize is grown under rainfed conditions more often than rice and wheat. Of the roughly 138 million hectares sown to maize in the world, 82 percent is rainfed, while 18 percent is irrigated. Developing countries occupy over 60 percent of the total maize area worldwide. The average rainfed maize yield in developed countries is 3.4 tons per hectare, while that of developing countries lags behind at 1.8 tons per hectare. Irrigated yields are higher at 4.2 tons per hectare in developed countries and 2.9 tons per hectare in developing countries. Rainfed maize production contributes 66 percent of the total yield in developing countries, 81 percent in developed countries, and 74 percent globally.

Global production of other grains including millet, sorghum, etc. is predominantly rainfed, with 156 million hectares being rainfed, accounting for 86 percent of the total world harvested area. Differing from wheat and maize, other grains have a lower fraction of rainfed area in developed countries than in developing countries, with 91 percent of total area planted using rainfed methods in developing countries, and 80 percent in developed countries. The average rainfed yield of other grains in developed countries is 2.1 tons per hectare, while that of developing countries is much lower at 0.9 tons per hectare. Irrigated areas yield 3.5 tons of other grains per hectare in developed countries and 2.2 tons per hectare in developing countries. Rainfed production of other grains contributes 80 percent of total yield in developing countries, 71 percent in developed countries, and 74 percent globally.

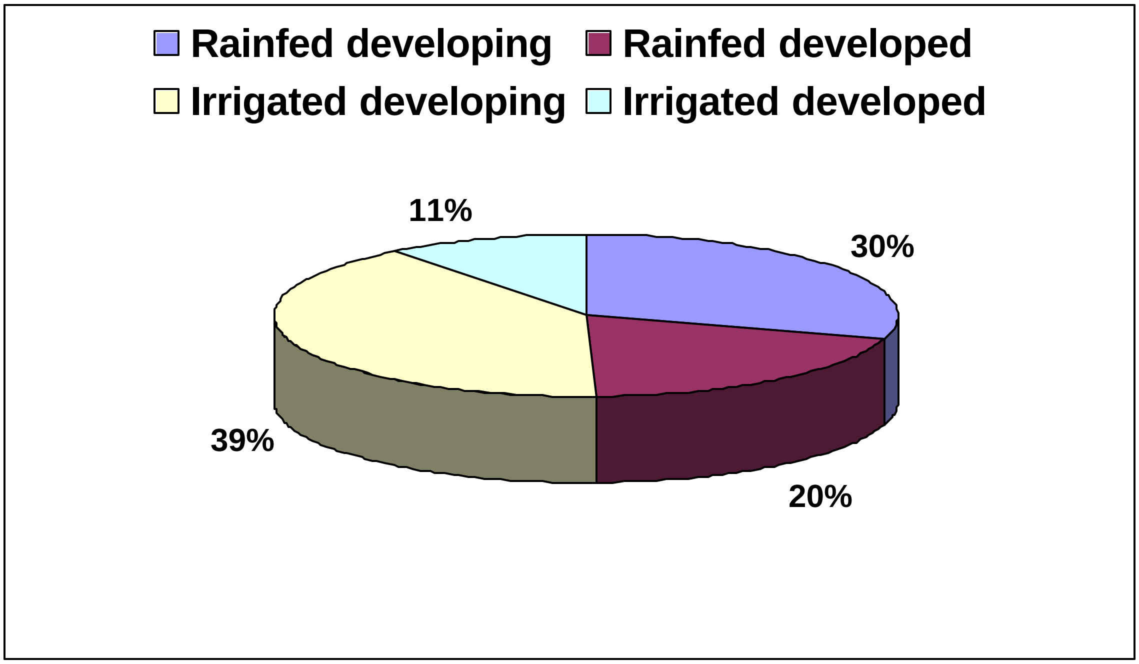
Approximately 62 million hectares of soybeans are harvested worldwide, of which 53 million hectares are rainfed. Developed countries plant 91 percent of the total soybean area using rainfed agriculture, while 80 percent of the area in developing countries is rainfed. Unlike cereal crops, rainfed and irrigated soybean yields are similar . In developed countries, the irrigated soybean yield is 2.7 tons per hectare, slightly higher than the rainfed yield of 2.2 tons per hectare; in developing countries, the irrigated yield is only slightly higher than the rainfed yield, with both at approximately 1.8 tons per hectare.

BASELINE PROJECTIONS

The IMPACT-WATER integrated water-food modeling framework, developed at IFPRI (Rosegrant and Cai 2000) is applied to assess the current situation and plausible future options of irrigation water supply and food security, primarily on a global scale. This model simulates the relationships among water availability and demand, food supply and demand, international food prices, and trade at regional and global levels. The world is divided into 69 spatial units, including single river basins in China, India and the US and aggregated river basins in other countries and regions. For each spatial unit, crop-wise water demand and supply are calculated, and then incorporated into separate rainfed and irrigated crop area and yield functions. Eight food crops are considered: rice, wheat, maize, other coarse grains, soybeans, potatoes, sweet potatoes, and cassava and other roots and tubers.

The baseline scenario presented here is based on our best estimates of the policy, investment, technological, and behavioral parameters driving the food and water sectors. Irrigation plays a dominant role in cereal production in developing countries, with nearly 60 percent of future cereal production in developing countries coming from irrigated areas, accounting for four-fifths of the growth in global irrigated cereal production. However, IMPACT-WATER projects that irrigated and rainfed production will each account for about one-half of the increase in cereal production between 1995 and 2021-25.

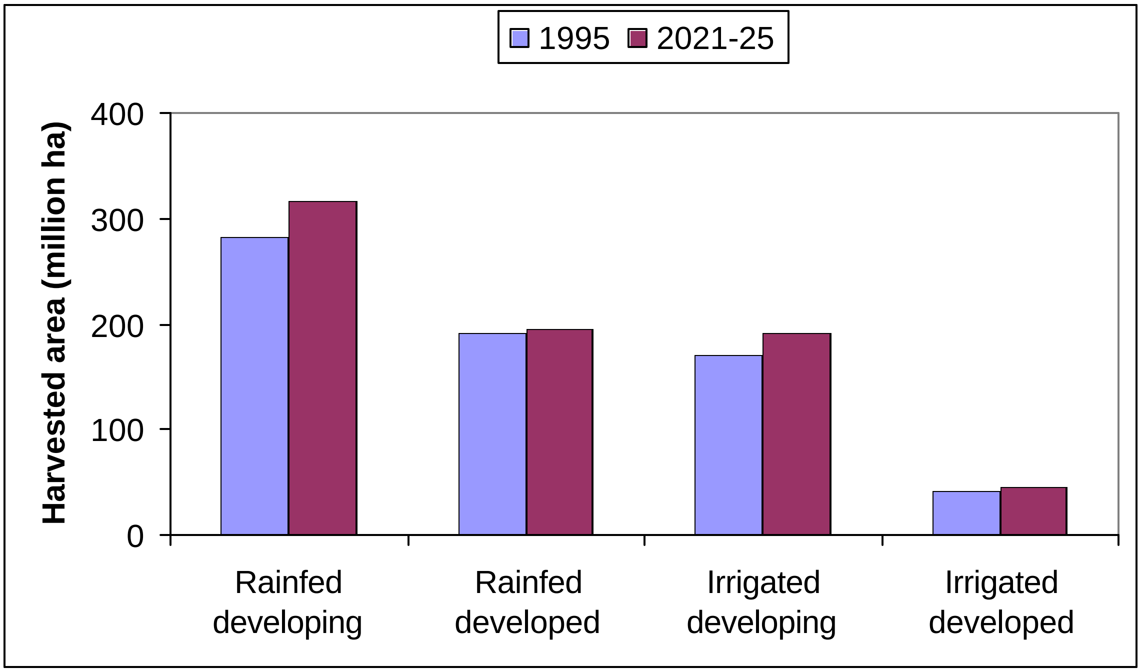
Figure 1--Share of irrigated and rainfed production in cereal production increase, 1995-2021/25



The strong contribution to overall cereal production from rainfed areas differs from previous estimates which have projected that as much as 80 percent of the additional food supplies required to feed the world over the next 30 years could depend on irrigation (IIMI 1992).

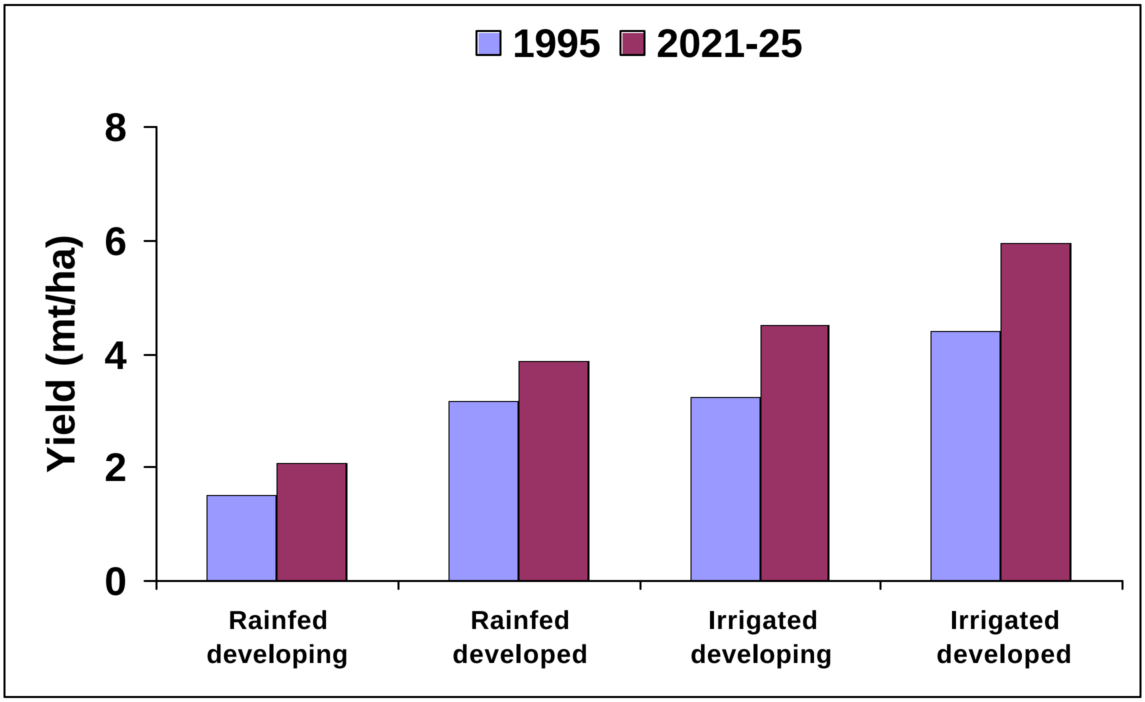
The importance of rainfed cereal production is in significant part due to the dominance of rainfed agriculture in developed countries. More than 80 percent of cereal area in developed countries is rainfed, much of which is highly productive maize and wheat land such as that in the Midwestern United States and parts of Europe (Figure 2).

Figure 2--Cereal harvested area, 1995 and projected 2021/25



The average rainfed cereal yield in developed countries was 3.2 metric tons per hectare in 1995, virtually as high as irrigated cereal yields in developing countries. These rainfed cereal yields in developed countries are projected to grow to 3.9 metric tons per hectare by 2021-25 (Figure 3).

Figure 3—Cereal yields, 1995 and projected 2021/25



Rainfed agriculture remains important in developing countries as well. While rainfed yields in developing countries are projected to increase only from 1.5 metric tons per hectare to 2.1 metric tons per hectare by 2021-25, rainfed area in developing countries will account for 43 percent of total cereal area, only slightly lower than the percentage in 1995.

IMPACT-WATER utilizes hydrologic data (precipitation, evapotranspiration, and runoff) to recreate the hydrologic regime of 1961-91 (Alcamo 2000). Non-irrigation water uses, including domestic, industrial, and livestock water uses are projected to grow rapidly. Total non-irrigation water consumption in the world is projected to increase from 370 km^3 in 1995 to 620 km^3 in 2025, an increase of 68 percent. The largest increase of about 85 percent is projected to occur in developing countries. Irrigation water demand is estimated and projected based on crop evapotranspiration and effective rainfall (estimated on a monthly basis), irrigated area, and water use efficiency. Globally, irrigated harvested area for cereals is estimated to be 221 million hectares in 1995, and growth is projected to be slow, with a total increase of 24 million hectares for irrigated cereals by 2025. The increase in total irrigated harvested area is slightly higher, with an increase from 355 million hectares in 1995 to 417 million hectares in 2025. Instream and environmental water demand is accounted as committed flow that is unavailable for other uses, and ranges from 15 percent to 50 percent of the runoff depending on runoff availability and relative demands of the instream uses in different basins.

On the supply side, for future years up to 2025, we assume increases in water management efficiency, reservoir storage and water withdrawal capacity, based on estimates of current investment plans and the pace of water management reform. Table 2 shows the area and yield growth rate between 1995 and 2025 for rainfed rice, wheat, maize, other grains, and soybeans in selected countries and aggregated regions under the baseline scenario.

Table 2(a)—Rainfed Area and Yield Growth Rates For Rice For Selected Countries and Regions

	Area (*million ha*)		Annual Growth Rate	Yield (*mt/ha*)		Annual Growth Rate
	1995	**2025**	**Percent**	**1995**	**2025**	**Percent**
USA	0.0	0.0	0.00	0.00	0.00	0.00
15 European Countries	0.0	0.0	0.00	0.00	0.00	0.00
Other Developed	0.0	0.0	-0.07	1.48	1.70	0.47
China	0.6	0.6	0.00	3.61	4.25	0.54
East Asia (excl. China)	0.3	0.2	-1.49	1.55	1.80	0.46
India	24.7	15.9	-1.46	1.44	1.88	0.89
South Asia (excl. India)	3.0	2.8	-0.21	1.37	1.98	1.24
Southeast Asia	21.4	21.7	0.04	1.46	2.20	1.37
Latin America	3.7	3.6	-0.16	1.27	1.76	1.10
Sub-Saharan Africa	5.2	6.8	0.90	0.86	1.51	1.90
W. Asia & N. Africa	0.0	0.0	0.00	0.00	0.00	0.00
Developed	0.0	0.0	-0.07	1.48	1.70	0.47
Developing	58.9	51.5	-0.45	1.41	1.99	1.17
World	58.9	51.5	-0.45	1.41	1.99	1.17

Table 2(b)—Rainfed Area and Yield Growth Rates For Wheat For Selected Countries and Regions

	Area (*million ha*)		Annual Growth Rate	Yield (*mt/ha*)		Annual Growth Rate
	1995	**2025**	**Percent**	**1995**	**2025**	**Percent**
USA	23.3	24.4	0.16	2.31	3.14	1.03
15 European Countries	13.0	12.7	-0.09	5.20	5.59	0.24
Other Developed	54.1	55.2	0.07	1.95	2.68	1.07
China	8.2	5.1	-1.57	2.80	3.68	0.91
East Asia (excl. China)	0.1	0.1	0.05	0.64	0.77	0.61
India	7.0	4.0	-1.86	1.57	2.07	0.92
South Asia (excl. India)	1.2	1.0	-0.55	0.81	1.28	1.56
Southeast Asia	0.0	0.0	-1.63	0.47	0.54	0.47
Latin America	8.1	11.1	1.07	2.05	3.74	2.02
Sub-Saharan Africa	1.4	2.0	1.13	1.47	2.51	1.79
W. Asia & N. Africa	21.2	23.7	0.37	0.00	0.00	0.00
Developed	90.4	92.3	0.07	2.51	3.20	0.82
Developing	55.5	56.3	0.05	1.61	2.22	1.08
World	145.9	148.7	0.06	2.17	2.83	0.89

Table 2(c)—Rainfed Area and Yield Growth Rates For Maize For Selected Countries and Regions

	Area (*million ha*)		Annual Growth Rate	Yield (*mt/ha*)		Annual Growth Rate
	1995	**2025**	**Percent**	**1995**	**2025**	**Percent**
USA	24.2	25.6	0.19	7.75	11.95	1.45
15 European Countries	3.0	2.5	-0.56	7.83	9.26	0.56
Other Developed	11.6	11.9	0.10	3.14	4.19	0.96
China	14.0	16.3	0.51	4.36	6.14	1.15
East Asia (excl. China)	0.2	0.2	-1.05	2.52	3.12	0.71
India	5.1	4.7	-0.21	1.29	2.05	1.55
South Asia (excl. India)	1.0	1.0	0.10	1.54	2.38	1.47
Southeast Asia	7.9	8.1	0.09	2.04	3.38	1.70
Latin America	25.8	30.5	0.55	2.17	3.06	1.15
Sub-Saharan Africa	20.1	25.3	0.77	1.18	1.83	1.48
W. Asia & N. Africa	0.7	0.5	-1.08	0.00	0.00	0.00
Developed	38.7	40.1	0.11	6.38	9.47	1.33
Developing	74.8	86.7	0.49	2.23	3.24	1.25
World	113.5	126.7	0.37	3.65	5.21	1.20

Table 2(d)—Rainfed Area and Yield Growth Rates For Other Grains For Selected Countries and Regions

	Area (*million ha*)		Annual Growth Rate	Yield (*mt/ha*)		Annual Growth Rate
	1995	**2025**	**Percent**	**1995**	**2025**	**Percent**
USA	7.2	7.2	-.03	3.09	4.75	1.45
15 European Countries	10.0	8.2	-0.67	3.35	3.85	0.46
Other Developed	6.8	7.1	0.13	2.57	4.41	1.82
China	3.4	3.3	-0.14	2.29	3.43	1.36
East Asia (excl. China)	0.2	0.2	0.14	2.50	3.58	1.21
India	25.5	25.1	-0.05	0.84	1.30	1.49
South Asia (excl. India)	0.5	0.5	0.00	0.90	1.31	1.24
Southeast Asia	0.4	0.4	0.24	0.96	1.39	1.22
Latin America	4.1	4.9	0.57	2.16	3.54	1.65
Sub-Saharan Africa	43.1	63.9	1.33	0.67	1.07	1.55
W. Asia & N. Africa	12.1	13.4	0.35	1.29	1.96	1.41
Developed	63.0	61.5	-0.08	2.14	2.81	0.92
Developing	93.0	115.4	0.72	0.92	1.39	1.36
World	156.0	176.9	0.42	1.41	1.88	0.96

Table 2(e)—Rainfed Area and Yield Growth Rates For Soybeans For Selected Countries and Regions

	Area (*million ha*)		Annual Growth Rate	Yield (*mt/ha*)		Annual Growth Rate
	1995	**2025**	**Percent**	**1995**	**2025**	**Percent**
USA	23.0	24.9	0.27	2.54	3.56	1.14
15 European Countries	0.3	0.3	0.07	3.0	4.78	1.50
Other Developed	1.5	1.5	0.18	1.80	2.74	1.42
China	4.1	5.5	1.00	1.76	3.21	2.02
East Asia (excl. China)	0.4	0.4	0.27	1.30	2.11	1.63
India	4.3	5.9	1.01	0.95	1.82	2.20
South Asia (excl. India)	0.0	0.0	0.18	0.63	1.01	1.57
Southeast Asia	1.9	2.2	0.44	1.16	1.91	1.69
Latin America	17.2	21.9	0.81	2.10	3.57	1.80
Sub-Saharan Africa	0.2	0.2	0.81	1.22	1.96	1.58
W. Asia & N. Africa	0.0	0.0	0.00	0.00	0.00	0.00
Developed	24.8	26.8	0.26	2.50	3.53	1.15
Developing	28.1	36.1	0.84	1.79	3.10	1.86
World	52.9	62.9	0.58	2.12	3.29	1.47

Rainfed rice area in developing countries will decrease overall by 7.4 million hectares, with the largest reduction projected in India, although rainfed rice area is projected to increase slightly in some areas such as Sub-Saharan Africa (SSA).

Worldwide, rainfed wheat area is projected to increase slightly, with 68 percent of this increase expected in the developed world. The largest rainfed wheat area reductions are expected in China and India, while the major rainfed wheat area increases will in Latin America and West Asia and North Africa (although overall developing country rainfed area increases by only 0.8 million hectares). Maize rainfed area will increase significantly between 1995 and 2025, with a global net increase of 13.2 million hectares. Most of this increase takes place in developing countries, including 5.2 million hectares in SSA, 4.6 million hectares in Latin America, and 2.3 million hectares in China. Although rainfed area for other grains is expected to decrease slightly in the developed world, a global increase is projected primarily due to an increase in SSA of 20.9 million hectares. Additional rainfed soybean area will be developed for most countries and regions as shown in Table 2, with net global increase of 10.0 million hectares, of which the majority is expected in developing countries.

Projections of rainfed crop yield increases are based on our evaluation of the investments and potentials for improvements in water management, breeding research for rainfed areas, and the likely policies and investments in rainfed areas. The growth rate of rainfed cereal yield is in the range of 0.5 – 2.0 percent, with a global average of around 1.0 percent. Sub-Saharan Africa experiences the highest yield growth rates ranging from an annual growth rate of 2.0 percent for rice to 1.5 percent for maize. Crop yield performance has gradually improved in SSA over the past decade, and it is projected that continued improvements in technologies and policies will permit relatively strong growth from the very low yield levels in 1995. Latin America and Southeast Asia also experience relatively high yield growth. For all cereals excluding maize, yield growth rates are lower in developed than in developing countries.

Effective rainfall use for rainfed crops is assumed to increase by 3-5 percent in the baseline due to improvements in water harvesting and on-farm water management, as well as varietal improvement that shifts crop growth periods to better utilize rainfall. This is approximately equivalent to increasing crop evapotranspiration by 150 km^3.

RAINFED AGRICULTURE VS. IRRIGATED AGRICULTURE–CHANGES TO 2025

A comparison of the average rainfed and irrigated cereal area, yield, and production, the fraction of rainfed area, and fraction of rainfed production during 2021-25 (Table 3) with the same items for 1995 (Table 1) shows changes in these items, a reflection of the changing role of rainfed agriculture during 1995-2025 under the baseline scenario.

Table 3-- Rainfed and irrigated cereal area, yield, and production in 2025, and fraction of rainfed area and production

Countries/Regions	**Irrigated**			**Rainfed**				
	Area *(million ha)*	**Yield** *(mt/ha)*	**Production** *million/mt*	**Area** *(million ha)*	**Yield** *(mt/ha)*	**Production** *(million/mt)*	**Rainfed Area**	**Rainfed Production**
							Percent	
USA	8.5	9.94	84.8	57.6	6.12	352.7	87.1	80.6
15 European Countries	9.7	7.95	77.2	24.8	5.24	130.0	71.9	62.8
Japan	1.3	5.63	7.4	0.2	3.74	0.8	14.4	10.0
Australia	3.5	3.82	13.2	13.4	2.34	31.4	79.5	70.4
Other Developed	2.5	5.80	14.6	24.1	3.43	82.7	90.6	85.0
E Europe	7.3	5.52	40.4	21.0	3.10	65.1	74.2	61.7
Ce Asia	9.9	1.45	14.3	12.8	0.82	10.5	56.6	42.4
Rest Former USSR	12.2	2.55	31.2	54.9	1.81	99.6	81.8	76.2
Mexico	3.9	5.73	22.4	7.9	2.57	20.1	66.8	47.4
Brazil	1.2	3.96	4.7	26.7	2.79	74.4	95.8	94.1
Argentina	1.4	8.47	12.3	11.6	3.90	45.2	88.9	78.7
Colombia	0.4	4.98	1.9	1.1	2.57	2.9	74.5	60.1
Other Latin America	2.9	4.26	12.2	7.8	2.32	18.0	73.0	59.6
Nigeria	1.9	4.30	8.0	21.6	1.27	27.3	92.0	77.3
N. Sub-Saharan Africa	1.4	2.07	2.9	40.6	0.98	39.7	96.7	93.2
Africa	0.4	2.77	1.0	14.5	1.21	17.6	97.6	94.6
S Sub-Saharan Africa	1.0	2.43	2.3	10.6	1.33	14.0	91.7	85.9
E Sub-Saharan Africa	0.2	2.50	0.5	8.3	1.88	15.5	97.5	96.7
Egypt	2.5	8.20	20.4	0.0	0.00	0.0	0.0	0.0
Turkey	0.3	5.69	1.5	13.2	2.66	35.1	98.0	95.8

Table 3 (continued)--Rainfed and irrigated cereal area, yield, and production in 2025, and fraction of rainfed area and production

Countries/Regions	Irrigated			Rainfed				
	Area *(million ha)*	**Yield** *(mt/ha)*	**Production** *million/mt*	**Area** *(million ha)*	**Yield** *(mt/ha)*	**Production** *(million/mt)*	**Rainfed Area**	**Rainfed Production**
							Percent	
Other W Asia & N Africa	8.0	3.68	29.3	22.4	1.22	27.3	73.8	48.3
India	46.7	3.81	177.7	49.8	1.63	81.4	51.6	31.4
Pakistan	10.6	3.07	32.5	0.9	0.93	0.8	7.9	2.5
Bangladesh	6.4	4.03	25.8	1.6	2.03	3.3	20.1	11.2
Other S Asia	4.0	2.40	9.5	3.0	2.16	6.5	43.2	40.6
Indonesia	9.3	4.62	43.0	5.9	2.44	14.5	39.0	25.2
Thailand	2.3	2.95	6.7	9.1	2.08	19.0	80.1	74.0
Malaysia	0.4	3.51	1.4	0.3	1.78	0.5	41.9	26.8
Philippines	2.8	2.98	8.2	4.5	2.46	11.2	62.1	57.5
Vietnam	4.2	5.17	21.9	3.5	3.19	11.3	45.4	33.9
Myanmar	1.0	4.30	4.5	5.7	2.80	16.0	84.5	78.1
Other SE Asia	0.3	3.43	0.9	2.4	2.22	5.3	89.9	85.2
China	66.6	5.89	392.4	29.6	4.65	137.5	30.7	25.9
S Korea	0.9	5.04	4.4	0.1	6.01	0.8	12.7	14.7
Other E Asia	1.2	3.30	3.8	0.6	1.70	1.0	32.6	20.0
Rest of the World	0.0	1.92	0.0	0.0	0.59	0.0	83.1	60.3
Developed	45.1	5.96	268.8	196.1	3.89	762.4	81.3	73.9
Developing	191.8	4.52	866.6	316.2	2.08	656.8	62.2	43.1
World	236.9	4.79	1135.3	512.3	2.77	1419.2	68.4	55.6

Worldwide, rainfed cereal area in 2021-25 is projected to be 512 million hectares, an 8 percent increase over the area planted in 1995; the aggregated rainfed cereal yield is 27 percent higher than yield in 1995; and the total rainfed cereal production increased 37 percent over the production in 1995. Increases in irrigated area, yield and production by 2021-25 are expected to be slightly higher than rainfed increases, with an 11 percent increase in irrigated expected over 1995 levels, a 38 percent increase in yield projected, and a 53 increase in production expected over 1995 values. Rainfed cereal area still accounts for the majority of total harvested area and total cereal production in 2021-25, although irrigated area and production comprise slightly more of the totals than in 1995. The developing world maintains very similar fractions of rainfed area and production to the values in 1995, and experiences a yield growth of 0.57 tons per hectare. The developed world will experience slightly larger increases in the fraction of rainfed area and rainfed production, as well as a yield growth of 0.72 tons per hectare over 1995 levels. For more detailed results on the role of rainfed crops, Table 4 shows fractions of total area and production that is rainfed for rice, wheat, maize, total cereals, and soybeans in several countries and aggregated regions.

Table 4: Fractions of rainfed area and production to the total in 1995 and 2021-2025 of major cereals and soybeans for selected countries and regions

Rice	**Area**		**Production**	
	1995	**2021-25**	**1995**	**2021-25**
USA	0.00	0.00	0.00	0.00
15 European Countries	0.00	0.00	0.00	0.00
Other Developed	0.00	0.00	0.00	0.00
China	0.02	0.02	0.02	0.01
East Asia (excl. China)	0.17	0.11	0.07	0.04
India	0.58	0.43	0.44	0.28
South Asia (excl. India)	0.26	0.23	0.16	0.15
Southeast Asia	0.53	0.53	0.36	0.38
Latin America	0.56	0.52	0.35	0.35
Sub-Saharan Africa	0.81	0.77	0.68	0.64
W Asia & N Africa	0.00	0.00	0.00	0.00
Developed	0.00	0.00	0.00	0.00
Developing	0.41	0.38	0.24	0.22
World	0.40	0.37	0.23	0.22

Wheat	**Area**		**Production**	
	1995	**2021-25**	**1995**	**2021-25**
USA	0.93	0.94	0.87	0.88
15 European Countries	0.79	0.79	0.74	0.71
Other Developed	0.86	0.84	0.82	0.76
China	0.28	0.22	0.22	0.17
East Asia (excl. China)	0.24	0.25	0.17	0.17
India	0.28	0.19	0.18	0.12
South Asia (excl. India)	0.10	0.09	0.04	0.04
Southeast Asia	0.24	0.16	0.13	0.11
Latin America	0.89	0.91	0.80	0.87
Sub-Saharan Africa	0.78	0.75	0.73	0.71
W Asia & N Africa	0.81	0.81	0.63	0.59
Developed	0.86	0.85	0.81	0.77
Developing	0.47	0.46	0.33	0.31
World	0.66	0.64	0.57	0.53

Table 4 (continued): Fractions of rainfed area and production to the total in 1995 and 2021-2025 of major cereals and soybeans for selected countries and regions

Maize	**Area**		**Production**	
	1995	**2021-25**	**1995**	**2021-25**
USA	0.85	0.85	0.83	0.80
15 European Countries	0.75	0.70	0.72	0.63
Other Developed	0.82	0.80	0.76	0.71
China	0.61	0.58	0.54	0.46
East Asia (excl. China)	0.38	0.32	0.30	0.25
India	0.84	0.77	0.70	0.52
South Asia (excl. India)	0.50	0.50	0.50	0.47
Southeast Asia	0.95	0.92	0.88	0.86
Latin America	0.90	0.90	0.79	0.78
Sub-Saharan Africa	0.96	0.96	0.90	0.90
W Asia & N Africa	0.36	0.27	0.16	0.12
Developed	0.83	0.82	0.81	0.77
Developing	0.82	0.80	0.66	0.61
World	0.82	0.80	0.74	0.69

Total Cereals	**Area**		**Production**	
	1995	**2021-25**	**1995**	**2021-25**
USA	0.87	0.87	0.82	0.81
15 European Countries	0.73	0.72	0.68	0.63
Other Developed	0.82	0.81	0.76	0.72
China	0.30	0.31	0.26	0.26
East Asia (excl. China)	0.28	0.25	0.18	0.17
India	0.62	0.52	0.43	0.31
South Asia (excl. India)	0.22	0.21	0.14	0.14
Southeast Asia	0.61	0.61	0.45	0.47
Latin America	0.85	0.85	0.74	0.75
Sub-Saharan Africa	0.96	0.95	0.89	0.89
W Asia & N Africa	0.78	0.77	0.58	0.55
Developed	0.82	0.81	0.77	0.74
Developing	0.62	0.62	0.43	0.43
World	0.69	0.68	0.58	0.56

Table 4 (continued)--Fractions of rainfed area and production to the total in 1995 and 2021-2025 of major cereals and soybeans for selected countries and regions

Soybean	**Area**		**Production**	
	1995	**2021-25**	**1995**	**2021-25**
USA	0.92	0.92	0.91	0.90
15 European Countries	0.85	0.85	0.82	0.77
Other Developed	0.84	0.84	0.83	0.86
China	0.49	0.55	0.50	0.54
East Asia (excl. China)	0.95	0.95	0.94	0.95
India	0.90	0.94	0.87	0.92
South Asia (excl. India)	0.73	0.73	0.64	0.67
Southeast Asia	1.00	1.00	1.00	1.00
Latin America	0.92	0.94	0.89	0.92
Sub-Saharan Africa	0.25	0.27	0.49	0.52
W Asia & N Africa	0.00	0.00	0.00	0.00
Developed	0.91	0.91	0.91	0.90
Developing	0.80	0.84	0.80	0.85
World	0.85	0.87	0.85	0.87

ALTERNATIVE SCENARIO SPECIFICATION

The future outlook for water and food projected under the baseline, and the contribution of rainfed agriculture to this future, is dependent on policy and investment decisions on agricultural research, irrigation, water supply infrastructure, and other water resource investments, as well as the pace of water demand management improvement and the farmers' decisions regarding on-farm management and adoption of new technologies. But what would happen if improvements in effective rainfall use lagged, or there were significant cutbacks in irrigation development and water supply investments? Could more rapid growth in rainfed crop production compensate for reductions in irrigation and water supply investment compared to the baseline? Through alternative scenarios, we explore the impacts of these changes and other modifications in policy, technology, and investment. This section explores other possible situations in rainfed agriculture and food security. The alternative scenarios are defined as follows:

No improvement in effective rainfall use (NIER). Under the baseline scenario, we assume a 3-5 percent increase in effective rainfall use. This alternative scenario assumes no improvement in effective rainfall use. These results will show the impact of the assumed improvement in effective rainfall use under the baseline scenario.

Low investment in irrigation development and water supply but higher increase of rainfed area and yield (LIV-HRF). Due to global and regional environmental concerns, the increasing cost of irrigation investment, and current low prices of many crops grown with irrigation, projected increases in irrigated area and levels of infrastructure investment and water management improvement under the baseline may not be achieved over the projection period. This scenario assumes that the rate of increase in potential irrigated area will be one-third of those under the baseline scenario.

Additionally, reductions in the reservoir storage growth rates for irrigation and water supply, water use efficiency, and maximum allowable water withdrawal (MAWW) are implemented. The net increase of global reservoir storage for irrigation and water supply only increases by 396 km^3 between 1995 and 2025 under the *LIV-HRF* scenario compared to an increase of 690 km^3 under the baseline. Global average basin irrigation efficiency increases only to 0.57, compared to 0.61 under the baseline (global basin irrigation efficiency in 1995 is 0.55), corresponding to a water consumption savings of 23 km^3 under the *LIV-HRF* scenario compared to 115 km^3 under the baseline. The net increase in MAWW between 1995 and 2025 is only 301 km^3 under *LIV-HRF* compared to 742 km^3 under the baseline.

To examine the potential for rainfed production growth to compensate for the effect of reductions in irrigated area and irrigation water supply, we assume that rainfed area and yield increase to levels that can almost offset the reduction of irrigated production, and maintain essentially the same international trade prices. A larger increase is assigned to rainfed yield than area (because of limited potential for area expansion), and a larger increase is assigned to those basins, countries, or regions where irrigation effects are greater.

Low investment in irrigation development and water supply but high increase of effective rainfall use (LIV-HIER). This scenario looks at the possibility of increasing effective rainfall use to counteract the reduction of irrigated production due to low investment in irrigation development and water supply. Effective rainfall use gradually increases by 10-15 percent above 1995 levels from 1995 to 2025 in those basins/countries with rainwater shortages for crop production, including river basins in the western US, northern and western China, northern and western India, and countries in Northern Africa and WANA. An increase ranging from 5-10 percent is projected for other regions.

Groundwater overdraft phased out, combined with higher growth in rainfed production, including higher rainfed area, yield, and larger improvement of effective rainfall use (GW-HRF2). Many regions in the world, including northern India, northern China, some WANA countries, and the western US have experienced significant groundwater depletion due to pumping in excess of groundwater discharge (Postel 1999). This scenario assumes it is possible for regions and countries that are unsustainably pumping their groundwater to return to sustainable use in the future, with groundwater overdraft in these countries/regions gradually phased out over the next 25 years. To explore the potential to offset lower irrigated production due to reduced groundwater pumping in these countries and regions, under this scenario, we assume an additional rainfed area and yield increase and higher effective rainfall use in the countries or regions where groundwater overdraft occurs, while other countries and regions remain the same as the baseline scenario.

ALTERNATIVE SCENARIO RESULTS

Results from the baseline and alternative scenarios are compared in Table 5, in terms of rainfed and irrigated cereal area and yield, the fraction of rainfed cereal production for selected countries and regions, and international prices for cereals (all shown as averages from 2021-2025). Specific results from each alternative are discussed below.

Table 5--Comparing alternative scenarios to the baseline: average projections during 2021-2025

Irrigation Water Consumption (km^3)

	Baseline	NHER[a]	LIV-HRF[b]	LIV-HIER[c]	GW-HRF2[d]
China	337	337	292	292	293
India	230	230	180	180	217
SE Asia	88	88	63	63	88
Sub-Saharan Africa	61	61	33	33	61
Latin America	94	94	65	65	94
W Asia & N Africa	135	135	115	115	120
Developed	274	274	233	233	271
Developing	1,206	1,206	982	982	1,124
World	1,480	1,480	1,215	1,215	1,394

a) NIER - no improvement in effective rainfall use

b) LIV-HRF - low investment in irrigation development and water supply but higher increase of rainfed area and yield

c) LIV-HIER - low investment in irrigation development and water supply but higher increase of effective rainfall use

d) GW-HRF2 - Groundwater over draft phasing off and larger rainfed agriculture development, including higher rainfed area, yield, and larger improvement of effective rainfall use

Table 5 (continued)--Comparing alternative scenarios to the baseline: average projections during 2021-2025

Rainfed Area (million ha)

	Baseline	**NHER**[a]	**LIV-HRF**[b]	**LIV-HIER**[c]	**GW-HRF2**[d]
China	29.6	29.1	31.0	30.4	30.2
India	49.8	49.0	51.2	51.3	50.6
SE Asia	31.5	31.2	32.0	31.8	31.5
Sub-Saharan Africa	95.5	93.7	99.3	99.8	95.5
Latin America	55.1	55.1	55.9	55.5	55.1
W Asia & N Africa	35.6	34.9	36.6	36.7	35.6
Developed	196.1	194.8	196.3	200.6	196.2
Developing	316.2	312.5	322.1	325.0	319.8
World	512.3	507.4	518.4	525.6	516.0

Irrigated Area (million ha)

	Baseline	**NHER**[a]	**LIV-HRF**[b]	**LIV-HIER**[c]	**GW-HRF2**[d]
China	66.6	66.7	57.7	58.0	64.0
India	46.7	46.7	40.2	40.5	46.7
SE Asia	20.3	20.3	19.2	19.5	20.3
Sub-Saharan Africa	4.8	4.8	3.2	3.2	4.8
Latin America	9.8	9.8	7.8	7.9	9.8
W Asia & N Africa	10.7	10.8	9.6	9.7	10.3
Developed	45.1	45.4	42.8	43.2	44.9
Developing	191.8	192.2	169.2	170.5	187.9
World	236.9	237.5	212.0	213.7	232.8

a) NIER - no improvement in effective rainfall use

b) LIV-HRF - low investment in irrigation development and water supply but higher increase of rainfed area and yield

c) LIV-HIER - low investment in irrigation development and water supply but higher increase of effective rainfall use

d) GW-HRF2 - Groundwater over draft phasing off and larger rainfed agriculture development, including higher rainfed area, yield, and larger improvement of effective rainfall use

Table 5 (continued)--Comparing alternative scenarios to the baseline: average projections during 2021-2025

Rainfed Yield (mt/ha)

	Baseline	**NHER**[a]	**LIV-HRF**[b]	**LIV-HIER**[c]	**GW-HRF2**[d]
China	4.65	4.52	5.46	4.95	5.25
India	1.63	1.54	2.04	1.76	1.96
SE Asia	2.47	2.33	3.06	2.61	2.47
Sub-Saharan Africa	1.19	1.15	1.33	1.26	1.19
Latin America	2.92	2.90	3.14	3.03	2.91
W Asia & N Africa	1.75	1.71	1.92	1.84	2.04
Developed	3.89	3.82	4.23	4.10	3.90
Developing	2.08	1.99	2.40	2.23	2.22
World	2.77	2.68	3.09	2.94	2.86

Irrigated Yield (mt/ha)

	Baseline	**NHER**[a]	**LIV-HRF**[b]	**LIV-HIER**[c]	**GW-HRF2**[d]
China	5.89	5.94	5.47	5.59	5.82
India	3.81	3.84	3.76	3.84	3.41
SE Asia	4.27	4.29	3.97	4.05	4.27
Sub-Saharan Africa	3.08	3.12	3.02	3.09	3.08
Latin America	5.46	5.50	5.15	5.24	5.45
W Asia & N Africa	4.78	4.80	4.80	4.87	4.01
Developed	5.96	6.00	5.65	5.72	5.95
Developing	4.52	4.55	4.28	4.36	4.33
World	4.79	4.83	4.55	4.64	4.63

a) NIER - no improvement in effective rainfall use

b) LIV-HRF - low investment in irrigation development and water supply but higher increase of rainfed area and yield

c) LIV-HIER - low investment in irrigation development and water supply but higher increase of effective rainfall use

d) GW-HRF2 - Groundwater over draft phasing off and larger rainfed agriculture development, including higher rainfed area, yield, and larger improvement of effective rainfall use

Table 5 (continued)--Comparing alternative scenarios to the baseline: average projections during 2021-2025

Rainfed Production (million mt)

	Baseline	NHER[a]	LIV-HRF[b]	LIV-HIER[c]	GW-HRF2[d]
China	137	132	169	151	158
India	81	75	105	90	99
SE Asia	78	73	98	83	78
Sub-Saharan Africa	114	108	132	126	114
Latin America	161	160	175	168	161
W Asia & N Africa	62	60	70	68	73
Developed	762	744	831	822	766
Developing	657	622	773	725	710
World	1,419	1,360	1,602	1,547	1,476

Irrigated Production (million mt)

	Baseline	NHER[a]	LIV-HRF[b]	LIV-HIER[c]	GW-HRF2[d]
China	392	396	315	324	372
India	178	179	151	156	159
SE Asia	87	87	76	79	87
Sub-Saharan Africa	15	15	10	10	15
Latin America	53	54	40	41	53
W Asia & N Africa	51	52	46	47	41
Developed	269	272	242	247	267
Developing	867	874	723	744	813
World	1,135	1,147	965	991	1,079

a) NIER - no improvement in effective rainfall use

b) LIV-HRF - low investment in irrigation development and water supply but higher increase of rainfed area and yield

c) LIV-HIER - low investment in irrigation development and water supply but higher increase of effective rainfall use

d) GW-HRF2 - Groundwater over draft phasing off and larger rainfed agriculture development, including higher rainfed area, yield, and larger improvement of effective rainfall use

Table 5 (continued)--Comparing alternative scenarios to the baseline: average projections during 2021-2025

Fraction of Rainfed Production (percent)

	Baseline	NHER[a]	LIV-HRF[b]	LIV-HIER[c]	GW-HRF2[d]
China	31	30	41	37	38
India	47	46	56	51	47
SE Asia	89	88	93	93	89
Sub-Saharan Africa	75	75	81	80	75
Latin America	55	54	60	59	64
W Asia & N Africa	74	73	77	77	74
Developed	43	42	52	49	47
Developing	56	54	62	61	58
World	31	30	41	37	38

World International Trade Prices (US$/mt)

	Baseline	NHER[a]	LIV-HRF[b]	LIV-HIER[c]	GW-HRF2[d]
Price of Rice	236	245	248	301	236
Price of Wheat	123	133	125	141	122
Price of Maize	106	114	108	124	105
Price of other grains	83	94	82	93	82

a) NIER - no improvement in effective rainfall use

b) LIV-HRF - low investment in irrigation development and water supply but higher increase of rainfed area and yield

c) LIV-HIER - low investment in irrigation development and water supply but higher increase of effective rainfall use

d) GW-HRF2 - Groundwater over draft phasing off and larger rainfed agriculture development, including higher rainfed area, yield, and larger improvement of effective rainfall use

Under *NIER*, in which the small increase in effective rainfall use under the baseline is eliminated, the international trade prices experience an increase of 4 percent for rice, 8 percent for wheat and maize, and 13 percent for other grains, than that under the baseline. There is a net reduction of rainfed cereal production of 47 million metric tons (a rainfed reduction of 59 million metric tons, which is partially offset by an increase of 12 million metric tons in irrigated areas due to higher cereal prices). The reduction of rainfed cereal production is most significant in West Asia and North Africa, Sub-Saharan Africa, China, and India, ranging from approximately 5 - 8 percent. Each of these countries and regions has large areas of low rainfall rainfed cereal production. Rainfed area harvested will decrease by 5.0 million hectares, of which 3.7 million hectares is in developing countries. The worldwide fraction of rainfed cereal production declines from 56 percent under the baseline to 54 percent under *NIER*.

Under *LIV-HRF*, with a strategy of offsetting the reduction in irrigation investment by investing in rainfed area development and increased yield, the international price will maintain approximately the same level as the baseline for all cereal crops except rice. It proved impossible to fully compensate for the loss of rice production , which has a high proportion of irrigated area. Compared to the baseline, this scenario results in a decline in global irrigation water consumption of 256 km^3, or 18 percent, and an irrigated cereal production decline of 170 million metric tons (140 million metric tons in developing countries). Rainfed area, however, experiences a slight increase of 6 million hectares (mostly in developing countries), an 11 percent rainfed yield increase(15 percent in developing countries), and an additional 183 million metric tons of rainfed production (116 million metric tons in developing countries).

China (and possibly India) will not be able to increase rainfed production enough to offset the irrigated production decline, because irrigated areas occupy a larger fraction of total cereal harvested area than rainfed areas. In developed countries, irrigated production will be less affected by low irrigation investment, and developed countries will be able to make up for the developing country decrease by increasing rainfed production. Under this scenario, developed country irrigated production declines by 27 million metric tons, while rainfed production increases by 69 million metric tons. Finally, under low irrigated and high rainfed agriculture, the fraction of rainfed production will increase significantly, to 62 percent globally, 52 percent in developing countries, and 77 percent in developed countries, compared to 56, 43 and 74 percent respectively under the baseline scenario.

The international trade prices (especially rice) under *LIV-HIER* are significantly higher than those under the baseline. This shows that the projected increase in effective rainfall water use cannot fully compensate for the irrigation decline due to low investment in irrigation development and water supply. Although the global rainfed cereal production under *LIV-HIER* is 128 million metric tons more than that under the baseline, irrigated production under *LIV-HIER* is 16 million metric tons lower than the baseline. In developing countries, the gap between the increased rainfed production and the reduction of irrigated production is 54 million metric tons. Although there is no reliable data to justify the potential increase of effective rainfall use in various regions of the world, we think the very large projected increase under this scenario will be difficult, if not impossible, to achieve.

Can the world phase out groundwater overdraft and compensate the irrigated production decline due to reduced groundwater pumping in some regions by increasing rainfed production? The modeling results from the *GW-HRF2* scenario, with less groundwater pumping and higher rainfed agriculture development, show that such a strategy is possible. Compared to levels under the baseline scenario, groundwater pumping will decline by 169 km^3, including a reduction of 11 km^3 in the US, 30 km^3 in China, 69 km^3 in India, 29 km^3 in WANA and 24 km^3 in other countries. Global groundwater pumping in 2025 falls to 753 km^3, representing a decline from the 1995 value of 817 km^3 and from the baseline 2025 value of 922 km^3.

Irrigated production will be reduced by 20.1 million metric tons in China, 18.4 million metric tons in India, 18 million metric tons in WANA, 1.6 million metric tons in developed countries, and 53.0 million metric tons in developing countries. These reductions can be offset by an increase in rainfed area and yield in those regions, but the required increase in yields would be very large. Compared to the baseline, average rainfed cereal yield would need to increase by 13 percent or 0.6 metric tons per hectare in China, 20 percent or 0.3 metric tons per hectare in India, and 0.3 metric tons per hectare in WANA; rainfed cereal area will increase by 0.6 million hectares in China, 0.8 million hectares in India, and 0.10 million hectares in WANA (Table 5). Such an increase would require substantial additional investments in agricultural research and management for rainfed areas compared to the baseline. Given the size of these required increases in rainfed cereal yield in China, India, and WANA, it may be necessary for these countries to also rely more on imports to meet the decline in irrigated production compared to the baseline.

SUMMARY AND CONCLUSIONS

Although irrigated production has made an increasing contribution to global food production (especially during the Green Revolution), rainfed agriculture still produces about 60 percent of total cereals. The baseline analysis shows that rainfed agriculture will continue to play a very important role in cereal production, contributing one-half of the total increase of cereal production between 1995 and 2025. However, appropriate investments and policy reforms will be required to enhance the contribution of rainfed agriculture, particularly if irrigation investment declines relative to the baseline scenario.

Water harvesting has the potential in some regions to improve rainfed crop yields, and can provide farmers with improved water availability and increased soil fertility in some local and regional ecosystems, as well as environmental benefits through reduced soil erosion. However, despite localized successes, broader farmer acceptance of water harvesting techniques has been limited, due to the high costs of implementation and higher short-term risk due to the necessity of additional inputs, cash, and labor. Water harvesting initiatives frequently suffer from lack of hydrological data and insufficient attention during the planning stages to important social and economic considerations, and the absence of a long-term government strategy for ensuring the sustainability of interventions. Greater involvement of farmers from the planning stages and the use of farmers for maintenance and data collection and provision of appropriate educational and extension support could help expand the contribution of water harvesting.

The rate of investment in crop breeding targeted to rainfed environments is crucial to future crop yield growth. Strong progress has been made in breeding for enhanced crop yields in rainfed areas, even in the more marginal rainfed environments. The continued application of conventional breeding and the recent developments in non-conventional breeding offer considerable potential for improving cereal yield growth in rainfed environments. Cereal yield growth in rainfed areas could be further improved by extending research both downstream to farmers and upstream to the use of tools derived from biotechnology to assist conventional breeding, and, if concerns over risks can be solved, from the use of transgenic breeding.

Crop research targeted to rainfed areas should be accompanied by increased investment in rural infrastructure and policies to close the gap between potential yields in rainfed areas and the actual yields achieved by farmers. Important policies include higher priority for rainfed areas in agricultural extension services and access to markets, credit, and input supplies. Successful development of rainfed areas is likely to be more complex than in high-potential irrigated areas because of their relative lack of access to infrastructure and markets, and their more difficult and variable agroclimatic environments. Investment in rainfed areas, policy reform, and transfer of technology such as water harvesting will therefore require stronger partnerships between agricultural researchers and other agents of change, including local organizations, farmers, community leaders, NGOs, national policymakers and donors.

LIST OF ABBREVIATIONS

CHA	Chemical hybridizing agent
CIMMYT	International Maize and Wheat Improvement Center
CSIRO	Commonwealth Scientific & Industrial Research Organization
GMO	Genetically modified organism
GW-HRF2	Groundwater overdraft phased out, combined with higher growth in rainfed production, including higher rainfed area, yield, and larger improvement of effective rainfall use
GxE	Genotype by environment
HI	Harvest index
ICARDA	International Center for Agricultural Research in the Dry Areas
IFPRI	International Food Policy Research Institute
IIMI	International Irrigation Management Institute
IRRI	International Rice Research Institute
LFA	Less-favored area
LIV-HIER	Low investment in irrigation development and water supply but high increase of effective rainfall use
LIV-HRF	Low investment in irrigation development and water supply but higher increase of rainfed area and yield
MAWW	Maximum allowable water withdrawal
MoALD	Ministry of Agriculture and Livestock Development, Kenya
MV	Modern variety
NERICA	New Rice for Africa
NIER	No improvement in effective rainfall use
OPV	Open-pollinated variety
SI	Supplemental irrigation
SSA	Sub-Saharan Africa
TV	Traditional variety
WANA	West Asia and North Africa
WARDA	West Africa Rice Development Association

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