Help for Developing Countries in a World of Rising Grain Prices

Thomas A. Lumpkin
Director General. International Maize and Wheat Improvement Center (CIMMYT)

Keywords: agricultural research, climate change, world population, agricultural efficiency

Abstract

Humanity is entering a precarious era as world population and consumption are growing faster than crop production with nearly all growth occurring in the developing world. Global food production must increase by 70% by 2050 and in the next 50 years world will need to produce as much food as has been produced in the history of mankind. At the present time rising poverty, food prices, and food insecurity are impacting world stability. Issues include underinvestment in agricultural research; the impact of climate change on agricultural systems; and resource degradation such as loss of topsoil and fertilizers. The solution will involve improved and more diverse cropping systems; more emphasis on precision agriculture; increase information and communication technology; tapping latent genetic potential; improved efficiency of photosynthesis, nutrients, and water use; biotic stress resistance; increasing nutritional quality; and improved postharvest handling. The successful implementation will require global initiatives and partnerships as well as concerted vision and political will.

FOOD SECURITY: CONVERGING ISSUES, CHALLENGES, AND OPPORTUNITIES

Felista Mateo is slight woman who stands just over five feet tall. She is a 37-year old single mother of four children. There is nothing imposing or striking about her, but Felista, and others like her, are key to one of the world's most pressing problems. Felista is a farmer. Traditionally, in her small Tanzanian village, women do not own land. Felista is an exception. After receiving special approval from the village council, she acquired a small plot from her father. With her inheritance, Felista joined the ranks of millions of subsistence farmers worldwide. Unwilling to accept convention, Felista embraced new farming techniques while her neighbors refused. She planted an unusual crop, pigeon pea, to assure a year-round harvest. For her main crop, maize, the region's staple food crop, she tried a type of seed that needed less water.

Had Felista failed, the results would have been devastating. For farmers like Felista there is no back-up plan, no food stamps, no public welfare, no forgiveness for bad decisions. There is either adequate food or there is scarcity. That is the reality. Fortunately, Felista did not fail. With help from local and global research and development organizations, she prospered. She not only grew enough food to feed her family but had extra to sell. Today, she is expanding her operations. Her children are thriving. Her neighbors, with guidance from experts, are now experimenting convinced they, too, can create a better life.

There are millions of farmers like Felista. They work small parcels of land using modest means. High-quality seed and fertilizer are luxuries. Sophisticated machinery is a fantasy. They look to the sky for rain and to leaders for better policies. Their crops survive at the mercy of Mother Nature. Droughts, insects, and disease are always a threat to their food security. Despite their impressive work ethic, these farmers are among the most vulnerable poor in the world. Many are hungry, and getting hungrier.

Humanity is entering a precarious era. Between 1975 and 1985 the world production of maize, wheat, and rice grew more than twice as fast as population. During the Green Revolution that swept across Asia, India's wheat harvest doubled in just four years. Schools were temporarily closed to store the excess grain. The world may never see anything so dramatic again.

Today, the opposite dynamic is at work. World population and consumption rates are growing faster than crop production. By 2050, the world will increase to more than 9 billion people. Nearly all the growth will happen in the developing world. The largest generation in the history of the Earth is coming of age today. Half the world is less than 30 years old. The challenge is to feed their children and their children's children. This implies increasing global food production by 70% by 2050. In the next 50 years the world will need to produce as much food as has been produced in the history of mankind.

POPULATION GROWTH AND GROWING AFFLUENCE

Based on the report by the UN Food and Agriculture Organization (FAO, 2009) the world's population will reach 9.1 billion in 2050, 34% more than today. Nearly all of this population increase will occur in developing countries. Those countries are also home to the poorest and most vulnerable people, in terms of lacking resilience to shocks like sudden increases in food prices (Fig. 1; Bassett and Winter-Nelson, 2010).

In countries like China and India, rising incomes and urbanization are causing major shifts in diets (Gulati and Dixon, 2009). The growing middle class is substituting eggs, dairy products, and chicken for rice and wheat. The increase in maize demand will be acute in Asia—an 87% rise from 162 million tonnes in 1995 to 303 million tonnes in 2020. Nor can the demand for maize as food be dismissed. Rapid population growth on ever-shrinking plots in Asia, and persistent poverty in areas where the high-yielding maize is an important staple for the poor (especially parts of South Asia), will continue to exert an upward pressure on food maize demand.

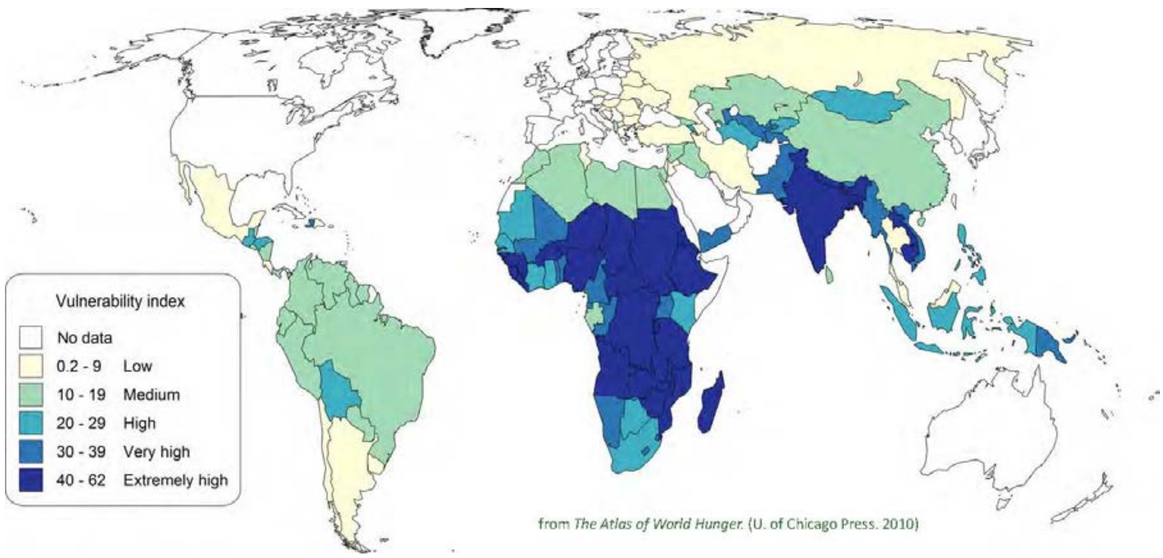

Fig. 1. Despite progress, hundreds of millions in developing countries still suffer from poverty and vulnerability to shocks like sudden increases in food prices.

To feed the larger, more urban and richer population and accommodate all other demands for food, feed, biofuel, and industrial products, farmers must boost staple crop production by 70%. In developing countries, 80% of the necessary production increases must come from increases in yields and cropping intensity, and only 20% from expansion of arable land. A rapidly-increasing part of this demand is for vegetables and fruits.

POVERTY, RISING FOOD PRICES, AND FOOD INSECURITY

In 2008 world food prices sky-rocketed, basic grain exports were embargoed in a number of countries, and supplies were threatened as weaknesses in global grain markets were exposed. People took to the streets to protest tortilla prices in Mexico and the price of bread in Egypt; another dozen countries around the world suffered similar incidents. Worst of all, resource-poor consumers, who spend generally more than half their meager incomes on food, could afford less to eat.

Bad weather, biofuel demand, and even speculation were implicated, but in fact economists had predicted for years that a crisis would come. For example, upon releasing in May 2007 its projections for world grain supply and demand for 2007/08, the United States Department of Agriculture (USDA) said supplies would plunge to a 53-day equivalent—their lowest level in the 47-year period for which data existed. Lulled to complacency by a quarter century of cheap, subsidized food, consumers and governments have ignored all the warnings.

At the time of the crisis, World Bank President Robert Zoellick said that food price inflation could push at least 100 million people into poverty, wiping out all the gains the poorest billion had made during a previous decade of economic growth. True to that prediction, in 2009 it was announced by the United Nations Food and Agriculture Organization (FAO) that the ranks of the hungry had surpassed 1 billion for the first time in human history. The continued fragility of food supplies and global markets was underlined again in 2010, when a heat wave and wild fires in Russia devastated the country’s wheat harvest, leading Russian policymakers to impose a temporary ban on national wheat exports and sending shock waves through global markets. By year’s end, the FAO Food Price Index (215) had returned to the high of 2008.

The suddenly exposed fragility of grain markets and supplies woke policymakers quickly to the need to invest more in domestic farm production capacity, through agricultural and rural development. The urgency of that need has been diluted somewhat by recent problems in financial markets. The economic meltdown has again lessened the capacity and inclination to fund public agricultural research and development. Nonetheless, the fact remains that unless countries invest in those areas and in enhanced market performance, food prices will escalate, driving millions of people who had recently become food-secure back into poverty and causing social unrest among both rural and urban poor.

TRENDS IN BASIC GRAIN PRODUCTION AND CONSTRAINTS: THE CASES OF WHEAT AND MAIZE

Demand for basic grains has risen briskly and will continue on the same path, driven by population and shifts in diets, but the global rate of growth in yields for the major cereal crops has slowed steadily in recent decades, from 3.2% per year in 1960 to 1.5% in 2000. The phenomenon is particularly pronounced in developing countries (Fig. 2).

Underinvestment in Wheat Research Slows Yield Growth

The case of wheat is illustrative and of special concern. Wheat was one of the first domesticated food crops and for 8,000 years has been the basic staple food of major civilizations in Europe, Western Asia, and Northern Africa. Today, wheat is grown on more land area—over 240 million hectares—than any other commercial crop and continues to be the most important food grain source for humans. Annual global production exceeds 0.6 billion tons. World trade for wheat is greater than for all other crops combined, and it provides more nourishment for humans than any other food source.

For many decades, the global average yield of wheat has increased, supported by effective international collaboration to deploy cutting-edge science alongside practical, multi-disciplinary applications. The work has made major contributions to improving food security and farmers' livelihoods in developing countries. For example, during the late 1950s and 1960s, researchers in Mexico, under the leadership of Dr. Norman Borlaug, developed the improved spring wheat germplasm that launched the Green Revolution in India, Pakistan, and Turkey (Reynolds and Borlaug, 2006). More recently, yields for wheat have continued to increase but their rise has slowed, lagging behind population increases. The world population growth rate from 1993 to 2000 was approximately 1.5%, whereas the growth rate in wheat production from 1985 to 1995 was only 0.9% (CIMMYT, 1996). During 1995–2005, annual growth in wheat yields slowed to 1.1%. Factors associated with the declining rate of wheat yield growth include the following:

- The relatively slow rise in private sector investments in wheat, compared to crops like maize, soybean, or rapeseed, which have benefitted from enormous private investments.
- The increasing frequency of drought and heat stress—in the latter case, particularly around grain filling growth stage.
- The reduced use in some settings of production inputs, as oil prices have driven up

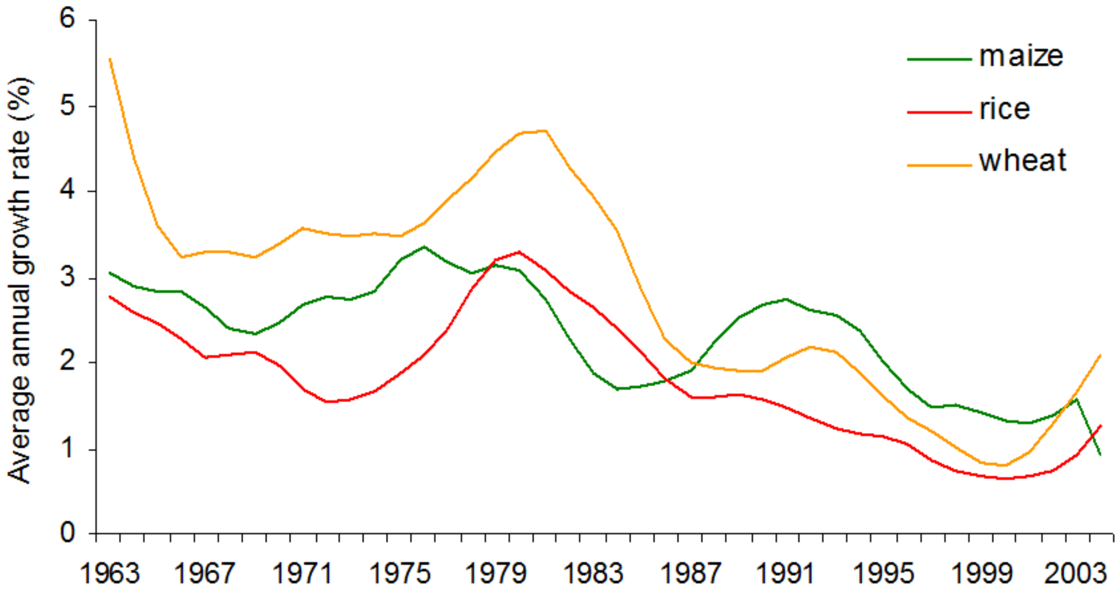

Fig. 2. Growth rates of yields for major cereals in developing countries is slowing. Source: World Bank, 2007.

the cost of fertilizer and of pumping irrigation water. In other settings, a lack of attention to crop management and resource depletion—including loss of soil fertility and falling water tables—has reduced total factor productivity: though farmers apply more nitrogen fertilizer, their yields increase little or tend to level off (Laxmi et al., 2007). The gradually falling price of wheat until very recently (Fig. 3) has been a boon to consumers, but has also reduced farmers' profit margins and their motivation to invest in better cropping systems for wheat.

Maize: A Multi-use Crop in Great Demand

Without exaggeration, maize is used directly or as a by-product in hundreds of ways. But for hundreds of millions of farmers and consumers in the developing world, it is known as a key source of food and livelihoods. Together with rice and wheat, maize provides at least 30% of the food calories of more than 4.5 billion people in 94 developing countries. Between now and 2050, the demand for maize in the developing world will double, and by 2025 maize will have become the crop with the greatest production globally and in the developing world.

Maize is produced on nearly 100 million hectares in 125 developing countries and is among the three most widely grown crops in 75 of those countries (FAOSTAT, 2010). About 67% of the total maize production in the developing world comes from low and lower middle income countries; hence, maize plays an important role in the livelihoods of millions of poor farmers. They grow maize for food, feed, and income in 24 diverse and mostly rainfed farming systems, accounting for about 90% of the total area. They are often too poor to afford irrigation and are exposed to significant risks of production and income

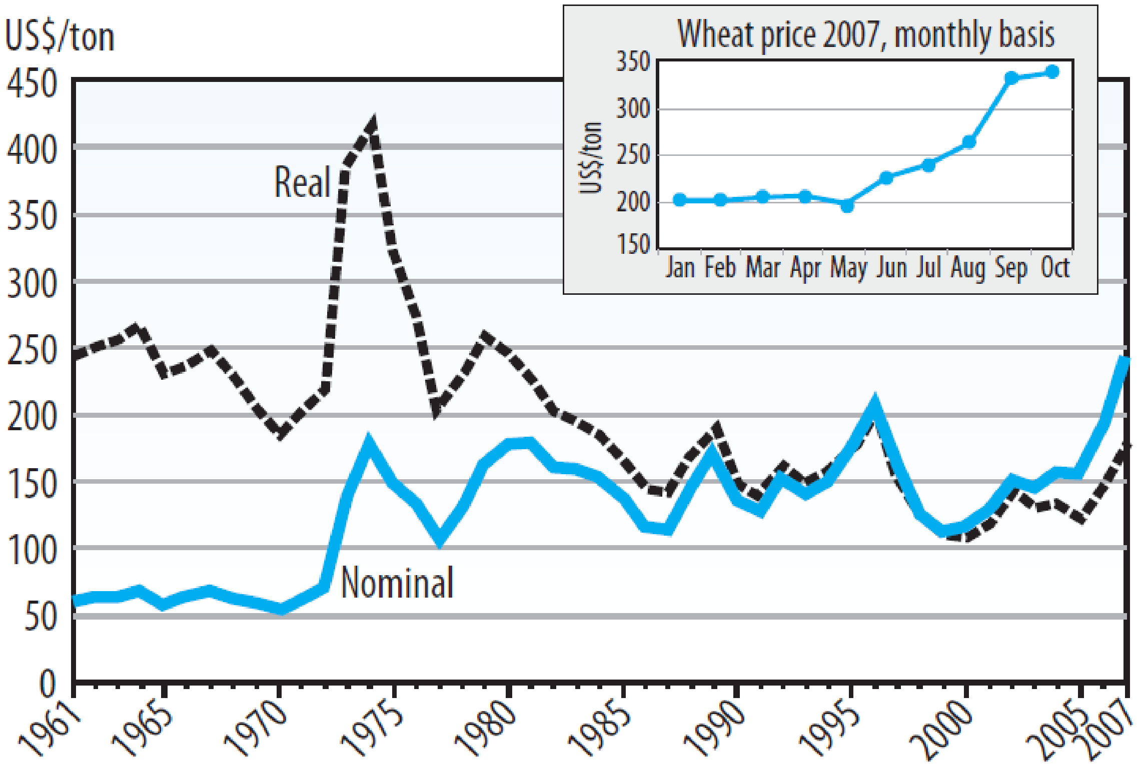

Fig. 3. Real and nominal international prices of wheat, 1961–2007. Source: USDA, Wheat Outlook, various issues.

failure. So it is not surprising that one-third of all malnourished children are found in systems where maize is among the top three crops (Hyman et al., 2008). Often with few other income opportunities than their farmstead, these farmers need options to increase and stabilize incomes from more productive, resilient and sustainable farming approaches that are adapted to future climates. Women play a significant role in maize production and maize-based systems.

1. Competing Uses for a Staple Grain. Affordable food is among the most basic human rights, and in that respect, maize is critical, ranking third after rice and wheat as a source of calories in the diets of developing country populations (FAOSTAT, 2010). Cheaper than either of those grains, maize is especially important for more than 900 million low-income consumers—the number of poor earning less than $US 2 per day (Population Reference Bureau, 2010; Worldbank, 2010)—who live in African, Asian, and Latin American countries where maize is among the three most important food crops. As described above, rapid economic growth over the past decade in highly-populated regions in Asia, the Middle East and Latin America has increased demand from more affluent consumers for poultry and livestock products, as well as the demand for maize as an industrial raw material, including its use for biofuel.

2. The Market is Responding, to the Detriment of the Environment and the Poor. Farmers, governments, and input suppliers have responded to the expanding demand for maize. During 2003–08 maize production increased annually by 6.0% in Asia, 5.0% in Latin America, and 2.3% in sub-Saharan Africa (FAOSTAT, 2010). Nonetheless, these increases fell short of what was needed to prevent price hikes in 2008 and by the end of 2010.

Part of the response to demand has involved bringing new land into cultivation, increasing maize areas in Asia and Latin America by 3.5% annually (FAOSTAT, 2010, referring to data from 2003–08). But FAO estimates that only 12% of the future increase in arable land in developing countries can be achieved through area expansion without exacting unacceptably high environmental costs (Bruinsma, 2009). At the current rate of area expansion, maize will eat up "its share of land" in less than five years; henceforth, maize expansion will come at the cost of crop diversity, forests, and eroded hill slopes.

A significant portion of the production increases is driven by government fertilizer subsidies, rather than by farmers adopting more sustainable and efficient practices. Expanding production through subsidized fertilizer has consequences on government budgets, if one considers that fertilizer prices are expected to increase strongly over the next two decades, as inputs for their production become depleted (Cordell et al., 2009). If fertilizers are not used more effectively and governments are no longer able to sustain fertilizer subsidies, the world will see food prices escalating much more drastically in the 2020–30s than is currently the case. Implementing more (or less) effective fertilizer use practices for food crops will have large effects on fertilizer reserves, environment pollution, and soil depletion (Heffer, 2009).

Regarding effects on the poor, production shortfalls in global maize supplies and increasing input prices have grave consequences for developing countries. Along with prices of other commodities, maize prices have almost doubled over the past 10 years (Index mundi, 2010) and may do so again by 2050. Such increases will impose great hardship on the poor, as the food price surges of 2008 and 2010 have made abundantly clear. In addition, lagging domestic production will place a huge and politically risky burden on developing country economies, driving up their maize imports from 5% of today's demand to 24% in 2050, a proportion that will be priced at around $US 30 billion (Rosegrant et al., 2008).

FUTURE CHALLENGES: CLIMATE CHANGE

Climate change is high on political, social, and scientific agendas: hardly a day passes without reference to its impacts or causes appearing in the media. The Fourth Assessment of the Intergovernmental Panel on Climate Change (IPCC FAR, 2007) concluded that "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level." The report classifies the warming trends as "very likely" (i.e., >90% probability) due to the observed increase in anthropogenic greenhouse gas emissions. These changes are occurring across continents in a relatively consistent manner. Atmospheric concentrations of the three principal greenhouse gases—carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—have all increased markedly since 1750, CO_2 principally due to the burning of fossil fuels and the others, to a considerable degree, as a result of agricultural activities. Global warming and associated changes in rainfall distribution and the increase in CO_2 will undoubtedly impact agricultural systems.

Wheat

Climate change may affect wheat production through the direct effects it has on yield via physiological processes, through changes in production systems such as earlier sowing dates or increased irrigation, and by changing the area under production, as regions become more or less suitable for wheat. General global trends, derived from meta-analysis of several simulation studies as reported by IPCC TAR (2001) and supported by the IPCC FAR (2007), include a slight increase in yields at mid- to high-latitudes, if moderate mean temperature increases (1–3°C) occur. However, further warming, even in temperate regions, causes yields to decrease, according to the models. In subtropical and tropical regions, wheat is often already near its limit of maximum temperature tolerance, so small temperature increases (1–2°C) will dramatically reduce yield, especially in the breadbasket of Southern Asia. Thus, the overall picture is one of decreasing wheat yields at lower latitudes, offset by increasing yields at mid- to high-latitudes under moderate warming. Similarly, Parry et al. (2004), who also considered grain market dynamics, highlighted increasing polarization between developed countries and low-latitude developing regions. Overall total global potential for food production is projected to increase under moderate (1–3°C) warming scenarios, but to decrease with any additional warming (same conclusion in both IPCC assessments).

Regarding crop yields, wheat is sensitive to temperature increases, but effects depend on background ambient temperature, stage of crop development, and cultivar. Increasing temperatures usually hasten crop development and shorten the grain-filling period, which severely reduces grain yield. Lawlor and Mitchell (2000) reported that a 1°C temperature increase during grain-filling shortens this period by 5% and proportionally reduces harvest index and grain yield. Extremes of temperature at sensitive developmental growth stages are especially detrimental: temperatures above 30°C at anthesis can damage pollen formation and reduce yield.

The rice-wheat cropping belt of the Indo-Gangetic Plains provides a clear example of how changing climates may affect the areas where wheat is sown (Fig. 4). Studies (summarized in Dixon et al., 2009) show how much of this currently high-potential wheat production area—which cuts across four countries, covers nearly 13.5 million hectares, and is the breadbasket of Southern Asia—will by 2050 likely become too hot for profitable, high-yielding wheat cropping. Considering the compounding impact of depleted ground water and increasing irrigation costs, this could result in the politically risky prospect of Southern Asia having to import as much as a quarter to a third of its wheat by 2050.

Western Asia and Northern Africa have the highest per capita wheat consumption. Imports as well as yield losses and year-to-year production swings will increase in these regions, due to rising temperatures, more severe weather extremes and decreasing water availability.

A key factor in wheat's marketability—grain quality—will undoubtedly suffer from the effects of global warming. Higher temperatures will reduce the grain-filling period, an effect often associated with reduced grain size. Although protein concentration would increase due to less translocation of carbohydrate relative to nitrogen, the net effect would be reduced quality. There also is evidence for a decline in grain protein under elevated CO_2 levels (Kimball et al., 2001; Ziska et al., 2004), presumably due to greater availability of carbohydrates for grain-filling (a protein dilution effect).

1. Important Side-effects of Climate Change: Evolving Wheat Diseases. Weeds, insects, and diseases reduce actual world wheat production by an estimated 28% (Oerke, 2006). More than a third of the losses from these biotic constraints is caused by fungal diseases (equivalent to $US 15 billion at 2007 international prices), and most of that is due to the three rusts of wheat: stem rust, leaf rust, and yellow rust. Though actual production losses are already high, it is anticipated that they will rise due to increased abiotic stresses caused by global climate change. Moreover, diseases and pests may also become significant constraints in regions where they have not been observed before or were previously not economically important.

The potential of new threats is exemplified by stem rust (*Puccinia graminis*), historically the most feared and widespread disease of wheat. Controlled for decades by genetic resistance, it has recently re-emerged as the most serious biotic threat to global wheat production. A new race of stem rust was identified in 1999 in Uganda (therefore

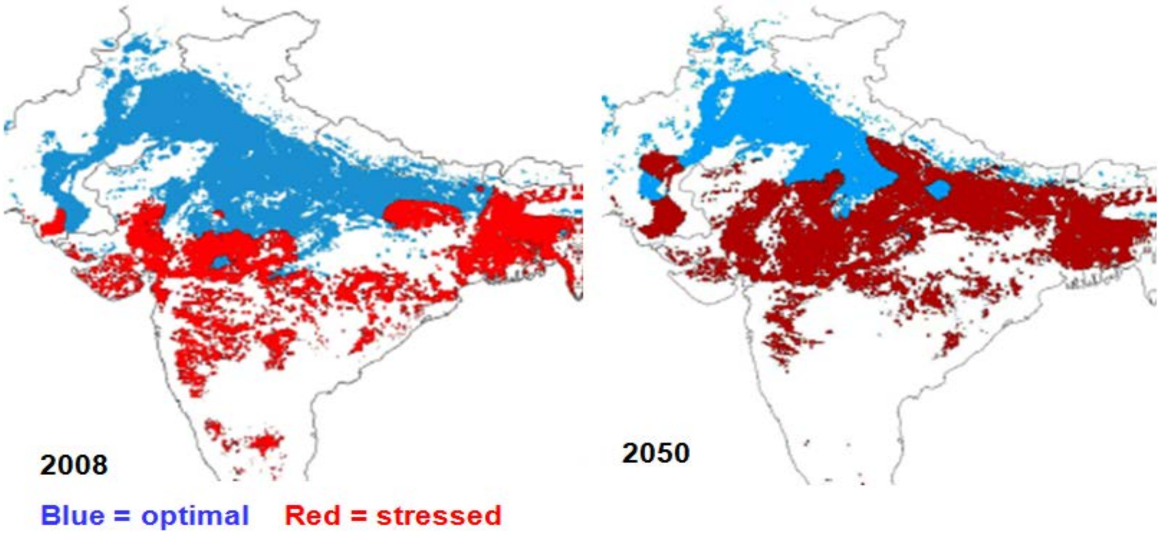

Fig. 4. Many currently optimal wheat cropping zones like the Indo-Gangetic Plains will become too hot for the crop by 2050.

named Ug99) and now threatens 120 million tons, or 20%, of the world's wheat in Central and Northern Africa, the Middle East and Asia, with a population of more than one billion people.

The best known pandemic of stem rust in the United States occurred in 1953–1954 and caused a 40% loss in spring wheat yields that would be worth $US 1 billion or more today. This led to the establishment of a response system comprising a collaborative international network of wheat improvement institutions, germplasm sharing, and strong human capacity and infrastructure dedicated to stem rust research. Through the development, release, and adoption of resistant wheat cultivars, there have been no stem rust pandemics over the five decades.

This has led to complacence and the atrophy of the response system. The emergence of Ug99 was a wake-up call, and a concerted, global research effort—the Borlaug Global Rust Initiative (www.globalrust.org/traction/permalink/about2)—was established to combat Ug99 and other wheat rusts. More than 30,000 wheat accessions, including major cultivars, have been evaluated at Ug99 hot spots in Kenya and Ethiopia, and results indicate that as much as 90% of the world's commercial wheat cultivars are susceptible. Fortunately, new resistant high-yielding wheat lines have also been identified and are now being distributed globally. The message though is that cereal rust pandemics cause losses in the hundreds of millions of dollars; only a fraction of these financial losses need be invested in research and breeding efforts aimed at controlling these diseases and re-establishing an effective global rust monitoring and surveillance system.

Maize

The impacts of climate change on all major crops will be greatest in the tropics and subtropics, with Africa and South Asia being particularly vulnerable as a result of the range of projected impacts, multiple stresses, and low adaptive capacity (Solomon et al., 2007; Hulme et al., 2001). Across various models, climate change is likely to reduce the productivity of current maize technologies, with the greatest losses predicted for southern Africa. In addition, climate change impacts on maize production will increase as the frequency of drought and other weather extremes increases and—as a recent analysis of CIMMYT international trials shows—the more frequently temperatures rise above 30°C. Extreme weather events will also alter the incidence, severity, and geographical distribution of pests, diseases and invasive weed species, thus affecting maize yield stability. New, stress tolerant germplasm is needed to help offset expected yield losses under projected climate change scenarios. Additionally, crop and soil management practices that reduce moisture stress, reduce greenhouse gas emissions, and enhance carbon sequestration will have important effects in climate change adaptation and mitigation.

One of the expected threats of climate change is more frequent and severe drought. With most maize production dependent on rainfall, the crop is particularly vulnerable to drought and its yields fluctuate more widely from year to year than is the case for rice and wheat, which are more commonly irrigated. Production fluctuations, whether at local, regional or global level, give rise to price hikes and food shortages. Already now, the probability of failed seasons in farming systems where maize is among the three most important crops varies between 8 and 35% (Hyman et al., 2008). And as irrigation costs are increasing, temperatures rising, and land getting scarcer, many farmers in Asia are switching from irrigated wheat and rice to maize, raising it with reduced irrigation or under rainfed conditions. For Africa particularly, the impacts will be highly variable, with southern Africa suffering worse damage while other regions (such as the East African Highlands) may see improved conditions for maize production.

FUTURE CHALLENGES: RESOURCE DEGRADATION AND SHORTAGES

Soil Degradation

An anonymous saying states that “Man, despite his artistic pretensions, his sophistication, and his many accomplishments, owes his existence to a 15 cm layer of topsoil and the fact that it rains.” Those words point up the paramount importance of farmers applying appropriate crop management practices that not only generate cost-effective, stable, crop production opportunities and allow cultivars to yield well, but also conserve the integrity and sustainability of the soil resource base. The first major study on human-induced soil degradation (Olderman et al., 1990) found that more than 300 million hectares of land worldwide had been strongly or severely degraded through deforestation, overgrazing, or improper agricultural management. The Green Revolution met the demand for food through intensification, helping to reduce hunger and poverty and, by increasing productivity per unit land area, to preserve forests, wetlands, biodiversity, and related ecosystem services (World Bank, 2007). But intensification brought other problems, among them inadequate care of soil and water resources. Nor do “traditional” farming systems offer solutions for growing human numbers and demand: in developing country areas not reached by the Green Revolution, agriculture has grown by bringing more, often fragile lands under cultivation, with an associated loss of forests, wetlands, and pastures.

Water Resources

Farming depends on water, either as rainfall or irrigation. Agriculture uses 85% of water consumed in developing countries, mainly for irrigation (World Bank, 2007). Even though irrigated farming accounts for only about 18% of the cultivated area in the developing world, it produces about 40% of the value of agricultural output. But water for irrigation is growing short. Many closed basins, such as the Colorado River in North America or China’s Yellow River, no longer flow to the sea. Major aquifers supporting large-scale agriculture—for example in India, Mexico, the USA—are being depleted at alarming rates, as recharging can no longer keep up with use. For rainfed agriculture, which is the most common system among small-scale farmers throughout the developing world, climate change studies forecast significant drying in many developing country areas, as well as more erratic and extreme rainfall events that contribute to run-off, erosion, and flooding.

Finite Supplies of Fertilizer

Since the 1960s, rising cereal yields have been driven by widespread use of irrigation, improved crop cultivars, and fertilizer. Access to and proper use of fertilizer is crucial for food grain production. Farmers’ low use of fertilizer—driven largely by the cost of this input and the riskiness of using it in rainfed settings—is a key constraint to farm productivity in sub-Saharan Africa and resource-poor areas of Latin America. Supplies of two important ingredients in balanced chemical fertilizer, nitrogen and phosphorus, will grow scarcer and more costly this century. The forecast for phosphorus is that about 90 years of global supplies can be extracted from current reserves, after which far more costly sources may have to be tapped (Scientific American, 2009).

OPPORTUNITIES FOR SUSTAINABLE FOOD PRODUCTION

As the world food situation is being transformed by new driving forces, farmers and researchers confront huge challenges but also emerging opportunities. It may be that the "easy gains" from crop improvement for basic grains have been exhausted. Clearly for rice and wheat, initial impacts from Green Revolution research accrued in high-input farming systems, where semi-dwarf cultivars responded well to increased use of fertilizers and irrigation. Later, spill-overs accumulated as improved cultivars spread from irrigated to higher-potential rainfed areas and then progressively into lower-potential rainfed areas. In the case of maize, most rainfed production zones yet await the right combination of improved cultivars and practices, public policies, and market conditions for more profitable farming.

Looking to the future, the following offer reasonable opportunities to meet the food needs of a growing world while making the best possible use of finite resources.

Improved, More Diverse Dropping Systems

A universal symbol of agriculture, the plow is deeply engrained in farmers' culture and identity. It may seem odd to suggest that farmers leave behind this implement and the convention it represents, but that is precisely the approach that now appears most logical and effective to reduce production costs, improve input-use efficiency, enhance system productivity, foster cropping diversification, and conserve the natural resource base, in most irrigated and rainfed farm settings. Hand-in-hand with reducing or eliminating tillage, farmers are being encouraged to retain enough crop residues on the surface to protect the soil from wind and water erosion, improve water productivity, and enhance sustainability, as well as to employ diversified crop rotations that help address weed, disease, and pest problems and enhance soil biological properties. Combined, the three principles—reduced or zero tillage, residue retention, and crop rotations—form the basis of "conservation agriculture."

Farmers adopt conservation agriculture initially because it significantly reduces their labor and production costs—that is, instead of multiple tractor passes or thousands of hoe-strokes to prepare the soil-bed and sow, seed is inserted directly into unplowed soils and residues in a single operation, saving time and money. In rainfed settings, conservation agriculture greatly improves water capture and infiltration, while reducing erosion, providing particularly dramatic benefits in dry years. In irrigated systems, in addition to saving labor and diesel, as much as 25% less water is required and fertilizer use efficiency is improved. Moreover, in intensive, multi-cropping settings like those of Southern Asia, turn-around time between crops is significantly reduced.

Longer-term benefits include enhanced soil structure and quality. Recent studies in the central highlands of Mexico show that conservation agriculture reduces the global warming potential of farming systems (Dendooven et al., in press).

Conservation agriculture is a complex, knowledge-intensive technology that requires the committed participation of farmers and diverse actors in value chains (e.g., input suppliers, farm implement manufacturers), as well as long-term technical backstopping. It normally requires a special implement to break through residues and place seed at proper depths in untilled soils, use of a herbicide for weed control in early stages of adoption, and use of rotations and other measures to manage diseases and pests. In many developing country farm settings, crop residues have economic value as forage, so farmers need support in managing a rational, minimal soil cover while satisfying competing needs for the residues. An effective approach to promote adoption of conservation agriculture is to create economic incentives by building on high-return components that raise productivity, create income opportunities, reduce vulnerability, and improve livelihoods. Such components promote investments in more sustainable practices by resource-poor farmers (Barrett et al., 2002; Shiferaw et al., 2009). Long-term trials as those of CIMMYT for maize and wheat systems in Mexico (Govaerts et al., 2009) and Asia form the theoretical basis for the successful application of conservation agriculture in specific locations.

The characteristics of conservation agriculture systems make them ideal for diversified intercrops and rotations.

1. Precision Agriculture. Practiced in the USA since the 1980s, precision farming is just beginning to gain a foothold in developing countries. While it is commonly accepted that nutrients are the major limiting factor to crop productivity in sub-Saharan Africa, fertilizer's agronomic potential is often unrealized because of poor land and crop husbandry practices. Many "poor" management practices (late application or inadequate doses) often stem from farmers' efforts to reduce risk (Kelly, 2006). It is crucial that farmers understand the factors that increase risk and/or reduce crop responsiveness to fertilizer (seeding date, weeding, tillage, timing of fertilizer application) if they are to achieve levels of management that allow the application of nutrients without undue risk.

While market and political risk are important, reducing the risk associated with weather, especially rainfall, through crop and soil management options and through better information on weather forecasts can raise the profitability of fertilizer use and crop productivity. Two particular avenues for addressing risk are response-farming techniques and simulation models; lessons from these tools need to reach many more farmers (Kelly, 2006).

In higher-productivity environments of Asia and Latin America fertilizer use is often excessive; this reduces the profitability of crop production and also increases environmental risks of nitrate leaching and eutrophication. The efficiency of use of nitrogen is commonly 30% or less, even though levels of over 80% are technically feasible (Raun and Johnson, 1999). Highly-efficient systems will depend on concurrently improving several avenues to efficiency—including application methods and fertilizer formulations, use of crop cultivars that are more efficient in nitrogen absorption, and methods to diagnose and apply needed levels of fertilizer, taking into account spatial variability in soils.

CIMMYT and partners for example, have been testing and promoting with wheat farmers in northwestern Mexico an infrared sensor that gauges the health and likely yield of the plants. The readings are run through a mathematical model to provide a recommendation about whether or not the crop requires a mid-season application of fertilizer. The approach boosts yields, saves farmers costly fertilizer, and reduces nitrous oxide emissions and nitrate run-off to aquifers and river deltas.

Reducing unproductive water losses is the key to increasing water-use efficiency in both irrigated and rainfed crop production. In both cases the evaporation from the soil surface is an important loss that can be reduced by surface mulch and planting geometry. In rainfed environments water run-off, often also associated with soil erosion, is another major loss of water that can be reduced or obviated by surface mulch and, if necessary on sloping land, physical structures to capture and/or manage water flow. In irrigated conditions, achieving efficient water distribution by leveling and field management (raised beds and furrow irrigation) can reduce water requirements—in Southern Asia it can be reduced over 40%.

As for most applied inputs, the "Law of Diminishing Returns" applies to irrigation water—large increases in efficiency can be achieved by applying less than optimum amounts of water, but applying this water at critical times. This also holds for rainfed areas where some supplementary irrigation can be applied; very large increases in yield and very efficient water use can be achieved with tactically applied supplementary irrigation. Crop cultivars often differ in their responses to reduced water, and so genotype × management (G×M) interactions will also be explored with respect to supplementary irrigation.

2. Information and Communication Technologies. In developing countries, traditional information sources like TV, radio, and newspapers can provide important generic information on agriculture, but are not able to address specific, local agro-climatic and economic realities. The information revolution has provided tools to bridge the physical distance between farmers and scientists, extension services and the private sector. Mobile phones are now one of the most widely used and fastest growing tools in rural areas of many developing countries. The increasing penetration of mobile networks and the explosion in handset numbers and subscribers presents an opportunity to deliver useful information more widely and rapidly to target groups. As one example, specialists at the International Rice Research Institute (IRRI) recently developed Nutrient Manager for Rice (NMRice), a decision tool for small-scale precision farming. This computer-based software guides farmers in applying fertilizer properly and efficiently in rice fields. Initially CD- or web-based, a new version allows transfer directly to a mobile phone application that provides field-specific fertilizer recommendations via SMS. The same platform provides ready access to information on finance and marketing opportunities and improved crop management practices.

Although this means of delivering agronomic and agribusiness information to farmers is still developing, it has already started demonstrating its potential in many countries. There are several examples in India and Africa of private enterprises, cooperatives, Non-Governmental Organisations (NGOs) and national research systems that are developing and testing special services to farmers to enhance access to key inputs, enable integration into markets, and support knowledge-based decision making based on timely, locally-tailored, accurate information.

Tapping Hidden Pools of Latent Genetic Potential

Biodiversity has provided a base for agriculture and the evolution of human societies since the dawn of civilization. Crop biodiversity—essentially, the genetic differences inherent in both native and improved food crop cultivars—has been assembled and conserved over many decades in seed banks. The bank collections have been used on many occasions to obtain genes for resistance to diseases and pests, as well as for other traits of value. However, the collections are vast and, due to the high costs and technological limitations, only a minute portion of the diversity has been put to practical use in crop breeding. CIMMYT and other organizations are beginning to leverage new genomics tools to identify, capture, and enable the use of many undiscovered alleles in seed banks and provide a new basis for breeders worldwide to accelerate breeding progress and meet impending food-production challenges.

The impact of new technologies on breeding is likely in seven main areas (Dixon et al., 2009): (1) more efficient access to beneficial genetic variation in diverse genetic resources; (2) more efficient transfer of beneficial variation from these genetic resources;

(3) introduction of novel genetic variation through genetic transformation; (4) more efficient manipulation of all sources of genetic variation in breeding programs using new genomic tools; (5) more rapid breeding systems based on double haploid technologies; (6) precision phenotyping systems that bring greater accuracy to all stages of the research and breeding process; and (7) more design-led breeding systems based on powerful new computer information systems linking advanced tools from genomics, biometrics, and conventional breeding.

Access To and Use of "Genetic Diversity" in the Broadest Sense

Farmers sowed 134 million hectares of genetically modified (GM) crops in 2009 (ISAAA, 2009). Transgenic crops are spreading more rapidly than any other agricultural technology in history—during 1996–2006 there was an 80-fold increase in their use, an average annual growth of 9 million hectares or 7%—which suggests that many farmers perceive important advantages to growing them. GM products and technologies are now used extensively in food production, from cheese to chickens, and components of GM soybean are widely used in processed food. Growth of biotech crops has been substantially higher in developing nations: 13% or 7 million hectares in 2009. As a result, almost half the global area of biotech crops is found in developing countries (ISAAA, 2009).

Surprisingly, this dramatic scale-up in production of transgenic crops is due almost entirely to two traits: herbicide tolerance and Bt-based pest resistance. However, there is now a wide range of transgenes being tested under controlled, contained field conditions, including transgenes for disease resistance, grain quality traits, and abiotic stress tolerance. Plant breeding that utilizes non-transgenic approaches will remain the backbone of crop improvement strategies, but genetically engineered cultivars and transgenes hold great promise, particularly for tackling certain intractable breeding problems and for meeting the challenges of food security and environmental protection (Ortiz and Hoisington, 2008). Transgenic approaches appear particularly useful where genetic diversity in a crop's primary gene pool is limited or where the environmental effect is very large. In those cases, a clear strategy for intellectual property management, regulatory approval and commercialization can be designed and funded. Country-specific strategies must be developed for transgenic cultivar deregulation and release, due to the differences in regulations and acceptance between them. Universities, advanced research institutes, and private companies will be essential partners whenever transgenic approaches will be taken. Because of the high cost of transgene development and deregulation, transgenic approaches require highly-promising events and strong partnerships to leverage the development pipelines and biosafety and deregulation investments made by major seed companies.

The following are key research areas and traits on which efforts can focus, to address the food security issues raised in this paper.

1. Photosynthetic Efficiency. Many approaches have been used to improve the wheat plant and raise its yield potential, but the fundamental obstacle—namely photosynthetic capacity—has hardly changed. Leading research institutes worldwide could achieve quantum leaps in the productivity of wheat, rice, and possibly other food crops by improving photosynthetic performance. For wheat, work would focus on sources of improved expression of radiation-use efficiency based on improved efficiency of CO_2 fixation at both whole plant (canopy) and cellular (Rubisco) levels. Genetic constructs ready for proof of concept include improved RuBP regeneration, Rubisco activase, Rubisco subunits with enhanced catalytic properties, and genes from algae and cyanobacteria to concentrate CO_2 in the wheat chloroplast compartment where Rubisco is located, to eliminate photo-respiration. Basic studies are also under way to increase rice yield by incorporating genes from the C_4 pathway (Surridge, 2002).

2. Nutrient/Water Use Efficiency. Diverse strategies are being followed to enhance the tolerance of crops to water-stress conditions, including the development of genetically-engineered cultivars. A large body of recent work has demonstrated that new opportunities exist to improve the adaptation of wheat to heat and drought stressed environments (Trethowan and Mujeeb-Kazi, 2008; Reynolds et al., 2009). Conventional breeding with a special focus on adaptation to marginal environments provides a necessary baseline in terms of genetic backgrounds into which new traits and their genes can be introduced. Research to identify and accumulate new and appropriate combinations of stress-adaptive traits must follow a systematic approach, since there is still much to learn about how potentially useful traits (and their genes) interact—with each other, with different genetic backgrounds, and across the vast range of environments (including warmer and drier environments predicted by climate change) in which they must be deployed.

For drought tolerance in small-grain cereal crops, initial research has focused on molecular mechanisms of water stress response in the model plant species *Arabidopsis thaliana* (Bennett, 2003), and particularly Dehydration-Responsive Element Binding genes (DREB). Other trait areas to explore—particularly for wheat—would include seed and embryo size, coleoptiles length for deep sowing, canopy growth for ground cover, strategic storage / allocation of assimilates, and deep and vigorous roots.

For maize, there have been tremendous advances in conventional breeding for drought tolerance, particularly in tropical maize (Bänziger and Araus, 2007), and for nitrogen use efficiency (CIMMYT, internal communication). Given the complex nature of the drought tolerance response, gene constructs with potential to complement conventionally-bred tolerance need to be tested for effectiveness in diverse germplasm backgrounds and stress environments.

3. Biotic Stress Resistance. Breeding for resistance to diseases and pests offers the most environmentally sustainable control approach, allowing farmers to reduce pesticide inputs, increase profit margins, and keep wheat prices affordable for urban and rural consumers. Resistance to lepidopteran crop borers based on *Cry* genes from *Bacillus thuringiensis* is a widely known example of transgenic pest control. Given the likelihood of pests and diseases overcoming host plant resistance based on single, major genes, however, a far better strategy for ensuring durable resistance is to pyramid multiple genes with differing and additive resistance effects, both from crops' primary gene pools and from other sources.

4. Nutritional Quality. Transgenic biofortification approaches for food crops holds promise. Researchable issues include the discovery, characterization, and use of genes for nutritionally valuable traits: protein, starch, and oil content/quality; grain levels of carotenoids, zinc, iron, phytic acid, anthocyanins, folate, and ascorbic acid. For forage crops, quality traits would include lignin and cellulose contents and digestibility. Again, effective public-private partnerships will be crucial for success.

The Importance of Post-harvest Handling

Safe storage of maize at the farm level directly impacts on poverty alleviation, food and income security, and prosperity for smallholder farmers. Without appropriate grain storage technologies, farmers are forced to sell maize when prices are low to avoid post-harvest losses from storage pests and diseases. They cannot add value to maximize gains from their harvest, nor use their harvest as collateral to access credit. Ultimately their food security is undermined.

Food security and safe storage at the farmer level go hand-in-hand. As well as providing food security for times of scarcity, effective grain storage is an inflation-proof savings bank; grain can be cashed as needed or used directly as a medium of exchange (i.e. in payment for work such as field clearing and weeding). Stored grain is also needed for farm-level enterprises such as poultry production, beer brewing, and cooking foods for sale. Appropriate low-cost storage technologies and high-yielding maize cultivars resistant to storage pests and diseases must be made readily available to farmers, so they can safely store and maintain quality of their produce.

Researchers have developed food crop cultivars with improved storage characteristics, including resistance to storage pests and fungi that produce deadly mycotoxins. More adequate and sustained funding for this work is required, as well as improved linkages among breeders, health sector experts, and policymakers. Finally, because mycotoxins cannot be seen, farmers are often unaware of their presence or the hazards of marketing or eating contaminated food. Addressing this requires cheap and robust field assay tools, as well as public awareness campaigns.

Low-cost, safe storage structures for small- and intermediate-scale farmers are being promoted by many organizations, including CIMMYT; their use needs to be scaled up through funded programs and specific policy support.

GLOBAL INITIATIVES AND PARTNERSHIPS: CONCERTED VISION AND POLITICAL WILL

In collaboration with other international centers involved in maize and wheat research, most prominently IITA and ICARDA, CIMMYT has recently developed a new strategy called the MAIZE and WHEAT CGIAR Research Programs (www.cimmyt.org /en/what-we-do/maize-and-wheat-cgiar-programs)—describing how the world's maize and wheat research and development community needs to work together to help secure food security, provide maize and wheat at prices affordable to the poor, and do so in the face of rising demands and climate change, while protecting the environment. The Programs offer a clear vision and concerted strategy, and describe expanded and reformulated interactions with research and development partners worldwide to implement a results-oriented maize and wheat research agenda. The International Rice Research Institute (IRRI) has recently launched the Global Rice Science Partnership (GRiSP; irri.org/our-science/global-rice-science-partnership-grisp), which outlines a global strategy and work plan for that important food crop.

These and other major new programs of the CGIAR (www.cgiar.org) are designed to address the concerns of farmers like Felista Mateo in Tanzania, as she and the world face daunting challenges to provide food security for everyone without consuming or destroying available resources. But they require the participation and support of many actors, including serious investment in agriculture and rural development on the part of developing countries themselves.

Literature Cited

Bänziger, M and Araus, J. 2007. Recent advances in breeding maize for drought and salinity stress tolerance. p. 587–601. In: Jenks, M.A., Hasegawa, P.M. and Jain, S.M.

(eds.), Advances in Molecular Breeding Toward Drought and Salt Tolerant Crops Springer, The Netherlands.
Barrett, C.B., Lynam, J., Place, F., Reardon, T. and Aboud, A.A. 2002. Towards improved natural resource management in African agriculture. p. 287–296. In: Barrett, C., Place, F. and Aboud, A. (eds.), Natural Resource Management in African Agriculture: Undersigning and Improving Current Practices. CAB Publ. Wallingford, UK.
Bassett, T.J. and Winter-Nelson A. 2010. The Atlas of World Hunger. University of Chicago Press, Chicago.
Bennett, J. 2003. Opportunities for increasing water productivity of CGIAR crops through plant breeding and molecular biology. p. 103–126. In: Kijne, J.W., Barker, R. and Molden, D. (eds.), Water Productivity in Agriculture: Limits and Opportunities for Improvement. CABI Publ. Wallingford, UK.
Bruinsma, J. 2009. The resource outlook to 2050: By how much do land, water and crop yields need to increase by 2050? FAO Expert Meeting on How to Feed the World in 2050. 24–26 June 2009, FAO, Rome.
CIMMYT. 1996. 1995/96 World Wheat Facts and Trends: Understanding Global Trends in the Use of Wheat Diversity and International Flows of Wheat Genetic Resources. CIMMYT. Mexico, D.F.
Cordell, D., Drangert, J.-O. and White, S. 2009. The Story of phosphorus: Global food security and food for thought. Global Environmental Change 19:292–305.
Dendooven, L., Patiño-Zúñiga, L., Verhulst, N., Luna-Guido, M., Marsch, R. and Govaerts, B. 2011? Global warming potential of agricultural systems with contrasting tillage and residue management in the central highlands of Mexico. (In press)
Dixon, J., Braun, H.-J., Kosina, P. and Crouch, J. (eds.). 2009. Wheat Facts and Futures 2009. CIMMYT, Mexico, D.F.
FAO. 2009. How to Feed the World in 2050. FAO High-Level Expert Forum, Rome, 12–13 Oct. 2009.
FAOSTAT 2010. Statistical databases and data-sets of the Food and Agriculture Organization of the United Nations. faostat.fao.org/default.aspx (accessed April 2010).
Govaerts, B., Sayre, K.D., Goudeseune, B., De Corte, P., Lichter, K., Dendooven, L. and Deckers, J. 2009. Conservation agriculture as a sustainable option for the central Mexican highlands. Soil Tillage Res. 103(2):222–230.
Heffer, P. 2009. Assessment of fertilizer use by crop at the global level 2006/07–2007/08. International Fertilizer Association, IFA. Paris, France. www.fertilizer.org/ifa/Home-Page/STATISTICS
Hulme, M., Doherty, R.M., Ngara, T., New, M.G. and Lister, D. 2001. African climate change: 1900–2100. Climate Res. 17:145–168.
Hyman, G., Fujisaka, S., Jones, S., Wood, P., de Vicente, S. Carmen, M. and Dixon, J. 2008. Strategic approaches to targeting technology generation: Assessing the coincidence of poverty and drought-prone crop production. Agr. Systems 98:50–61.
Index mundi. 2010. Monthly commodity prices. www.indexmundi.com (accessed 04 May 2010).
IPCC. 2001. IPCC Third Assessment Report: Climate Change 2001. www.ipcc.ch/
IPCC. 2007. IPCC Fourth Assessment Report: Climate Change 2007. www.ipcc.ch/
ISAAA. 2009. Global status of commercialized biotech/GM crops: 2009. The first fourteen years, 1996 to 2009. The Intl. Service for the Acquisition of Agri-biotech Applications (www.isaaa.org).

Kelly, V. 2006. Farmers' demand for fertilizer in sub-Saharan Africa. Discussion Paper 23. Agriculture and Rural Development. The World Bank, Washington, D.C.

Kimball, B.A., Kobayashi, K. and Bindi, M. 2002. Responses of agricultural crops to free-air CO_2 enrichment. Adv. Agron. 77:293–368.

Lawlor, D.W. and Mitchell, R.A.C. 2000. Wheat. p. 57–80. In: Reddy, K.R. and Hodges, H.F. (eds.), Climate Change and Global Crop Productivity. CAB Intl., Wallingford, UK.

Laxmi, V., Erenstein, O. and Gupta, R.K. 2007. Impact of zero tillage in India's rice-wheat systems. CIMMYT, Mexico, D.F.

Oerke, E.C. 2006. Crop losses to pests. J. Agr. Sci. 144:31–43.

Olderman, L.R., Hakkeling, R.T.A. and Sombroek, W.G. 1990. World map of the status of human-induced soil degradation: an explanatory note. Wageningen: Intl. Soil Reference and Information Centre; Nairobi: United Nations Environment Programme.

Ortiz, R. and Hoisington, D. 2008. Research and field monitoring on transgenic crops by the Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT). Euphytica 164:893–902.

Parry, M.L., Rosenzweig, C.A., Iglesias, M., Livermore, M. and Fischer, G. 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Global Environ Change 14:53–67.

Population Reference Bureau. 2010. prb.org/pdf09/09wpds_eng.pdf (accessed 05 May 2010).

Raun, W.R. and Johnson, G.V. 1999. Improving nitrogen use efficiency for cereal production. Agron. J. 91:357–363.

Raun, W.R., Solie, J.B., Johnson, G.V., Stone, M.L., Mullen, R.W., Freeman, K.W., Thomason, W.E. and Lukina, E.V. 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agron. J. 94:815–820.

Reynolds, C.R.P., Foulkes, J.M., Slafer, G.A., Berry, P., Parry, M.A.J., Snape, J. and Angus, W.J. 2009. Raising yield potential in wheat. J. Expt. Bot. 60:1899–1918.

Reynolds, M.P. and Borlaug, N.E. 2006. Impacts of breeding on international collaborative wheat improvement. J. Agr. Sci. 144:3–17.

Rosegrant, M.W., Msangi, S., Ringler, C., Sulser, T.B., Zhu, T. and Cline, S.A. 2008. International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description. International Food Policy Research Institute: Washington, D.C. www.ifpri.org/themes/impact/impactwater.pdf (accessed March 10, 2010).

Scientific American. 2009. Phosphorus: A looming crisis. June.

Shiferaw, B., Okello, J. and Reddy, V.R. 2008. Adoption and adaptation of natural resource management innovations in smallholder agriculture: reflections on key lessons and best practices. Environment, Development, Sustainability 11:601–619.

Solomon, S., Qin, D. Manning, M. Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds) 2007. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Univ. Press, Cambridge.

Surridge, C. 2002. Agricultural biotech: The rice squad. Nature 416: 576–578.

Trethowan, R. and Mujeeb-Kazi, A. 2008. Novel germplasm resources for improving environmental stress tolerance of hexaploid wheat. Crop Sci. 48:1255–1265.

Wada, N., Cheng, F., and Gulati, A. 2009. Chapter 1: Introduction and overview. In Gulati, A. and Dixon J., (eds.), Maize in Asia: Changing Markets and Incentives. Washington, D.C., and IFPRI and CIMMYT, Mexico, D.F.:

World Bank. 2010. data.worldbank.org/indicator/SI.POV.DDAY (accessed 05 May 2010).

World Bank. 2007. World Development Report 2008. World Bank, Washington, D.C.

Ziska, L.H., Morris, C.F. and Goins, E.W. 2004. Quantitative and qualitative evaluation of selected wheat varieties released since 1903 to increasing atmospheric carbon dioxide: Can yield sensitivity to carbon dioxide be a factor in wheat performance? Global Change Biology 10:1810–1819.