

PROVISIONAL

**Overview: Transitioning
Wheat Research
to Serve the Future Needs of
the Developing World**

J. Dixon, H.-J. Braun, and J.H. Crouch

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to Serve the Future Needs of the Developing World****J. Dixon, H.-J. Braun, and J.H. Crouch****Introduction**

For millennia wheat has provided daily sustenance for a large proportion of the world's population. It is produced in a wide range of climatic environments and geographic regions (see Table 1). During 2004-2006, the global annual harvested area of "bread wheat" and "durum wheat" (see Box 1 for a description of the different types of wheat) averaged 217 million ha, producing 621 million tons of grain with a value of approximately US\$ 150 billion.¹ About 116 million ha of wheat was grown in developing countries, producing 308 million tons of grain (FAO 2007) with a value of approximately US\$ 75 billion.² Wheat fulfills a wide range of demands from different end-users, including staple food for a large proportion of the world's poor farmers and consumers. The similarity between average yields in developed and developing regions is deceptive: in developed countries around 90% of the wheat area is rainfed, while in developing countries more than half of the wheat area is irrigated, especially in the large producers India and China. In addition, there are large differences in productivity³ among countries within the two groups of countries, and even among countries applying similar agronomic practices. For instance, among major rainfed producers (over one million ha), the average national yield ranges from about 0.9 t ha⁻¹ in Kazakhstan to 2.6 t ha⁻¹ in Canada and up to 7.9 t ha⁻¹ in the United Kingdom. Similarly, there are contrasts among irrigated producers, for example, India has an average yield of 2.6 t ha⁻¹ compared with 6.5 t ha⁻¹ in Egypt. Thus, there is clearly considerable scope for increasing productivity in many countries.

¹ Valued at monthly average 2007 international price, as represented by US HRW (hard red wheat) fob Gulf ports price.

² Valued at monthly average 2007 international price, as represented by US HRW (hard red wheat) fob Gulf ports price.

³ In this document, yield and productivity are used interchangeably, although yield is usually a partial productivity measure.

Box 1. Descriptions of the Different Types of Wheat

Bread wheat (*Triticum aestivum aestivum*) accounts for more than 90% of global wheat production and is grown on a substantial scale (over 100,000 ha) in more than 70 countries on 5 continents (Lantican et al. 2005). The main products include a great variety of leavened, unleavened and steamed breads, noodles, cookies, cakes, and breakfast cereals. **Spring bread wheat** accounts for roughly 70% of the 116 million ha sown to wheat in developing countries. **Winter bread wheat** requires vernalization, a temperature-related plant response mechanism that prevents these wheats, which are always sown in the late summer-autumn, from flowering before or during winter. In some areas with mild winters, such as in Australia, parts of China, India, West Asia and North Africa, Southern Africa, and South America, spring wheats are often sown in autumn, and often farmers wrongly refer to these autumn-sown spring wheat crops as winter wheats. At high latitudes with extreme winters, wheat production is based on spring wheats sown in the spring.

Durum wheat (*Triticum turgidum durum*) accounts for around 30 million tons, or 5%, of global wheat production, of which about 35% is produced in North Africa and West Asia, 25% in North America, and 30% in the EU. Most durum wheat production is based on spring varieties. Durum wheat is mostly used to produce semolina, pasta, and cracked wheat products such as couscous or bulgur. As it is a minor type of wheat, it is often incorporated with other wheats in national and global statistics, and for the most part is not given separate treatment in this document.

The relative importance of wheat as a staple in selected countries is displayed in Figure 1. Wheat provides 500 kcal of food energy per capita per day in the two most populous countries in the world, China and India, and over 1400 kcal per capita per day in Iran and Turkey. Overall across in the developing world, 16% of total dietary calories come from wheat (cf. 26% in developed countries), which is second only to rice in importance. As the most internationally traded food crop, wheat is the single largest food import in developing countries and, also, a major portion of emergency food aid.

Wheat made a significant contribution to the increase in global food production during the past four decades as total production rose steadily through the use of higher yielding, water- and fertilizer-responsive, and disease resistant varieties supported by strengthened input delivery systems, tailored management practices, and improved marketing (Braun 1998; Dixon et al.

2006); the increased grain production attributable to improved germplasm alone has been valued at up to US\$ 6 billion per year⁴ (Lantican et al. 2005). The increased production of wheat (and other staples) led to lower food prices (von Braun 2007) which contributed to the reduction in the proportion of poor in developing countries noted by Chen and Ravallion (2007). Looking to the future, global population is projected to steadily increase, albeit at a decreasing rate compared to the past century, to around 9 billion in 2050. The food and other needs of the growing population underpin the strong demand for cereals. The demand for wheat, based on production and stock changes, is expected to increase from 621 million tons during 2004-2006 to 760 million tons in 2020 (Rosegrant et al. 2001), around 813 million tons in 2030, and more than 900 million tons in 2050 (FAO 2006, 2007; Rosegrant et al. 2007); this implies growth rates of 1.6% during 2005-2020, 1.2% during 2005-2030, and 0.9% over 2005-2050. As can be seen from Figure 2, projections suggest that the demand for maize will grow faster than for wheat, particularly because of the strong demand for maize as animal and poultry feed, but also because of the increasing demand for biofuel maize. The demand for wheat, in turn, will grow faster than that for rice and will follow very closely the growth in global population over this period.

Drivers of Past Trends and Future Changes in Wheat Production

Past trends

The steady increase in wheat production has been due to increases in both area and yield. Production area continuously expanded in all regions for many decades until 1980, then contracted in Latin America until 1995 (see Figure 3). During 1995-2005 the growth in area was negligible in South Asia, where land has become scarce, while area growth has been slow in Central Asia and North Africa and Latin America. Moreover, with slower productivity growth than some alternative crops and, until recently, lower relative prices, wheat has been replaced by maize and high value crops in India, the US, and especially China, where the wheat area has decreased from a maximum of 27 million ha to 23 million ha. Some of these trends may be reversed in the near future in response to changes in relative yields and/or prices (FAO 2007).

For many decades, the global average yield of wheat has increased, supported by an effective International Wheat Improvement Network (IWIN), an alliance of national agricultural research

⁴ Valued at 2002 international wheat price, which was less than half the current prices.

systems (NARSs), CIMMYT, ICARDA, and advanced research institutes (ARIs) (see Box 2). This alliance has deployed cutting-edge science alongside practical multi-disciplinary applications, resulting in the development of germplasm that 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, 2006a; see also Box 3).

Box 2. International Wheat Improvement Network

Achievements in global wheat production during the second half of the 20th century were substantially fuelled by the collective efforts of the International Wheat Improvement Network (IWIN) [<http://www.cimmyt.org/Research/wheat/IWISFOL/IWIN.htm>], which is based on the free exchange of germplasm and data. Several hundred wheat researchers annually participate in this global network and evaluate new wheat germplasm from CIMMYT, ICARDA, and the TURKEY-CIMMYT-ICARDA Winter Wheat program. This germplasm is distributed through international nurseries targeted to specific agro-ecological environments and consisting of segregating populations, screening nurseries, and advanced yield trials (Dixon et al. 2006). Data collected from these screening sites across the world are returned to CIMMYT or ICARDA on a voluntary basis and then curated into public access databases [<http://www.cimmyt.org/wpgd>] and used to guide future breeding decisions. The IWIN utilizes novel biodiversity from global wheat related species while capturing the benefits of improved wheat germplasm from NARSs and ARIs.

The IWIN is a prime example of the long-term reinforcing benefits of collective action, where the motivation of scientists and breeders across the world to share germplasm and information benefits everyone and provides an important foundation for global wheat improvements in the future. The two-way flow of information empowers NARSs while strengthening the relevance of products from international breeding programs (Byerlee and Moya (1993).

Collaboration was extended during the 1970s to include Brazil, China, and other major developing country producers, and resulted in wheat varieties with broader disease resistance, better adaptation to marginal environments, and tolerance to acid soils. During the 1980s, an international collaborative partnership between Turkey, CIMMYT, and ICARDA was established for winter wheat improvement in developing countries (see Box 3). The IWIN

currently operates field evaluation trials in more than 250 locations in around 100 countries with the purpose of testing improved lines of wheat in different environments.⁵

Box 3. Beyond the Irrigated Spring Wheat Green Revolution of South Asia

The Green Revolution is generally associated with short-strawed, input efficient spring wheat (as well as rice) in South Asia, in particular India and Pakistan. However, there was also another type of “Green Revolution” in Turkey. In 1967, the Turkish Ministry of Agriculture and the Rockefeller Foundation established the National Wheat Improvement Program, which was supported by staff from CIMMYT and Oregon State University. In the same year, 22,000 tons of wheat seed were imported from Mexico into Turkey and, by the early 1970s, Mexican cultivars covered around 60% of the coastal spring wheat area and produced yields at least twice as high as those of local varieties.

Turkey’s winter wheat areas also experienced a “Green Revolution.” The combination of introducing new agronomic practices and improved cultivars,⁶ in particular the Russian cultivar Bezostaya, led to significant yield increases. By 1982, Turkey had doubled its national wheat production with average yields increasing from 1.1 to 1.8 t ha⁻¹, predominantly on rainfed land; it has been self-sufficient for wheat since then.

With the growing research capacity of NARSs in many major wheat producing countries, the number of wheat varieties released annually by developing countries doubled to more than 100 by the early 1990s (Lantican et al. 2005). The early improved varieties spread rapidly over the high potential production areas in most developing regions. As shown in Figure 4, widespread adoption occurred most rapidly in South Asia, especially in irrigated areas, followed by rainfed areas of Latin America; adoption has been slower in the Middle East and North Africa and sub-Saharan Africa because of drier, riskier environments and weaker institutions (Evenson and Gollin 2003b; Lantican et al. 2005). With such widespread adoption accompanied by yield increases, average annual rates of return on investments in wheat research averaged around 50% per year (Alston et al. 2000). In addition, the urban poor benefited substantially as production increases drove down wheat prices.

⁵ Since the 1950s, wheat programs in major OECD countries contributed to, and also benefited from, the International Wheat Improvement Network.

⁶ The term cultivar is used frequently through the document, in the same sense as variety.

Prior to the Green Revolution, the global average wheat yield was increasing at about 1.5% per annum: around 2.2% per annum in developed countries but less than 1% per annum in developing countries (see Figure 5 and Aquino et al., this volume); in the latter case, this was around one-third of the population growth rate. The Green Revolution boosted the growth of average wheat yields to 3.6% per annum in developing countries during 1966 to 1979. However, yield growth in developing countries slipped to 2.8% per annum during the period 1980 to 1994, and then dropped to 1.1% per annum during 1995 to 2005 (Figure 5 and Aquino et al., this volume), once again falling below the population growth rate.⁷ While poor productivity increases before the Green Revolution were compensated by expansion in production area, Figure 3 indicates that area growth during the 1995 to 2005 period was around 1% per annum in Latin America and close to zero in other developing country regions. It is noteworthy that a steady yield growth on the order of 1.7-1.8% per annum was maintained in developed countries until 1994 (even though wheat production is mainly rainfed in these areas), but halved to around 0.7% per annum during the 1995 to 2005 period. Some of the reasons for the reduced performance during 1995 to 2005 are discussed below.

To understand the causes for reduced performance after the mid-1990s, production data was disaggregated to the national level for the top 20 wheat producers. Figure 6 shows, for each of these countries, average national yield growth during the period 1966 to 1994 compared with that of the period 1995 to 2005.⁸ A useful reference point is the 1.6% growth rate, the approximate yield growth rate required to reach the projected wheat production level in 2020 (Rosegrant et al. 2001). Figure 6 shows that the initial 30-year period was a time of moderately rapid growth in wheat productivity in both developing and developed countries, although 14 of the 20 countries fell below the 1.6% growth rate. The USA and Canada performed especially poorly, with only 1% growth, although this also reflected the tendency to increasingly crop wheat in less productive areas. Overall, yield growth in the past decade (1995-2005) was lower than in the preceding 30-year period in 17 of the 20 countries; only Russia, Iran, and Kazakhstan showed improved performance.

⁷ While yield potential measured in breeders fields continued to grow constantly during past decades, a growth slowed in production due to various factors including high input costs, declining soil fertility and water, crop management, policies, and perhaps climate change. In many farming systems, the yield gap between farmers' fields and breeders' plots exceeds 40%.

⁸ Even the decade 1995-2005 is a relatively short period; it was noted that there was shift in yield growth rate in many countries around 1995.

As indicated in Table 2, only Pakistan and Iran had an average growth in productivity above 2% for the entire 40 years from 1966 to 2005. Some of the countries with yield growth rates below 1% per annum are major wheat exporters, e.g., Australia, USA, Canada, and France. Considering individual countries highlights a variety of reasons for lower recent performance, including the general decline in international wheat prices (affecting many countries), the collapse of agricultural services (e.g., in Ukraine), adverse climatic conditions (e.g., in Australia), and attractive diversification options (e.g., in Australia, EU, USA, Canada, Egypt, India, Turkey, and China). However, wheat remains part of the current cropping systems, and productivity may increase as break crops (such as legumes and oilseeds) improve soils and, consequently, wheat yields in some countries. Weakening domestic demand has also contributed to the decline of wheat (e.g., in China). Conversely, countries showing strong recent performance are characterized by effective domestic measures to enhance wheat production through a combination of better varieties, improved agronomy, and strong agricultural support policies (e.g., in Iran and Egypt).

While developing country wheat productivity growth exceeded that for all major crops during the 30 years preceding 1994, productivity growth has slowed during the past decade to an average level among major crops. The growth rate of many crops has slowed during the past decade, and some of the explanations noted above for poor or good wheat performance would apply to other crops. Figure 7 illustrates the relative yield growth performance of food crops in developing countries. During the 30-year period from 1966 to 1994, in the group of 10 major crops, only maize, wheat, soybean, and rapeseed exceeded 2% yield growth. These crops have benefited from strong public and private sector investments in breeding and crop management, as well as good national policy support. During this period, there was strong public support for food crops, prior to structural adjustment: the private sector invested heavily in maize, soybean, and rapeseed research in many developed countries, and the spillovers to developing countries were large (e.g., from the USA to South America). Meanwhile, wheat benefited from the international alliance of public sector research spanning both developed and developing countries. However, from 1995 to 2005, as annual growth in wheat yields slowed to 1.1%, seven other food crops performed better than wheat, although only three crops (rapeseed, groundnuts, and cotton) exceeded the 2% threshold. Interestingly, the yield growth rate of rice was around 20% lower than that of wheat in both periods. It is noteworthy that rapeseed exceeded 2% yield growth in

both periods, underpinned initially by strong public sector research, which led to a smooth transition to strong private sector investment in breeding, agronomy, processing, and marketing; for similar reasons, increases in soybean productivity have been robust. Also in less extensively bred crops, the exploitation of genetic diversity has often led to dramatic initial growth in productivity.

It would appear that factors associated with the declining rate of yield growth in wheat include the relatively slow rise in private sector investments during the last decade, and lower application of production inputs as oil prices have driven up the cost of fertilizer and of pumping irrigation water, while (until very recently) the price of wheat gradually fell. Additional reasons for the decline are the increasing frequency of droughts, plus a lack of attention to crop management and resource degradation, including loss of soil fertility and poor quality of irrigation water.

Real wheat prices (adjusted for inflation) have declined substantially over past decades (until 2007), as shown in Figure 8. This decline halted abruptly in 2007, when wheat stocks fell to a 30-year low, driving up market prices and wheat futures. This was partly due poor weather in major wheat producing countries including Australia, Canada, and China, and the shift of acreage from wheat to maize and canola, particularly in the USA and Western Europe, prompted by the soaring demand for bioenergy crops. Increases in oil prices have been a major contributing factor to spikes in wheat prices during the past four decades. However, there is now increasing uncertainty concerning medium-term price forecasts for wheat and other grains, due to volatility in market demand and climatic unpredictability; one of the most recent forecasts suggests an increase in the real price of wheat of approximately 40% by 2050 (Rosegrant et al. 2007).

As the world food situation is being transformed by new driving forces (von Braun 2007), wheat farmers and researchers are confronting major challenges but also emerging opportunities. It may be that the "easy gains" from wheat research have been exhausted. Clearly past impacts from wheat research were greater in high input farming systems, where semidwarf varieties responded well to increased use of fertilizers and irrigation. Later, spillovers accumulated as improved varieties spread from irrigated to higher-potential rainfed areas and then progressively into lower-potential rainfed areas (Byerlee and Moya 1993; Dixon et al. 2006). Looking to the future, will changing consumer preferences and strengthening market value chains create adequate new

markets for quality wheat that will justify increased attention to breeding for quality? Will molecular breeding improve the efficiency of field breeding and accelerate the release of dramatically more productive lines and varieties? Does genetically modified (GM) wheat have significant potential benefits for the industry and consumers? Will the impact of global climate change require major shifts in wheat research and breeding objectives? Are there improved soil and crop management technologies that would enable farmers to obtain the full benefit of new wheat varieties, while conserving the resource base for future generations of wheat farmers? Are there proven models of integrated “germplasm enhancement–improved crop management–more favorable policy environment” approaches that might be replicated in major wheat producing areas? These issues are examined in the following sections of this Overview and addressed in more depth in the ensuing chapters.

These are some of the issues that NARS managers and senior wheat researchers must now confront in order to select an optimal portfolio of strategic wheat research and breeding activities for the coming years that will have an impact on the ground during the coming decades. Until the dramatic expansion of demand for biofuels (maize) and the weather-induced supply problems in the past few years, the prospects for a reversal of the steady fall of the real prices of cereals, including wheat, appeared poor: now, as noted above, recent projections suggest a long-term increase in the real price of wheat (and other cereals). There are a number of trends and predicted key factors on which to base decisions: for example, the growing world population needs more food and more energy, and more feed grain to supply an ever increasing global demand for animal products; decreasing water supplies for agriculture and the effects of climate change are increasing the levels of abiotic stress across major wheat production areas; the application of biotechnologies is likely to offer new opportunities to increase yields provided the private sector is sufficiently engaged. In the following sections, we try to address some of the issues mentioned above, and present and discuss some alternative scenarios for evolution of the wheat industry over the next two decades. We then discuss major threats and opportunities of relevance to wheat researchers and breeders, and finally draw some conclusions regarding the most likely future priorities.

Drivers of future change

Science and technology. The availability of international public goods (IPGs) (including improved wheat germplasm, production technologies, and supporting institutions) developed from agricultural research is an important determinant of wheat productivity and the future of the wheat industry. The prime sources of new genetic variation to drive continued improvement of wheat remain wild species, landraces, and genetic stocks of wheat (wheat genetic resources), together with elite wheat lines and varieties. New trait development based on gene discovery and allele mining methods will greatly enhance the efficiency of identifying, introgressing, and manipulating genes for these traits in wheat improvement programs (see Crouch et al., this volume). During the past decade, conventionally developed "synthetic"⁹ wheat lines have become an increasingly important resource for breeders to quickly and efficiently introgress genes from certain wild species into their breeding programs. Genetically modified wheat varieties have not yet been approved for commercial production anywhere in the world. However, genetically engineered lines with transgenes for drought tolerance, disease resistance, herbicide resistance, or improved grain quality have been approved for field testing in a number of countries, including Australia, Canada, Germany, Switzerland, and the USA. To date, however, GM wheat has not been approved for commercial production anywhere in the world. Other complementary and critical IPGs to underpin the future of wheat are generated from cropping systems management research that increases input use efficiency and expands the range of production choices for sustainable agriculture. As wheat production becomes increasingly commercialized, institutional models for research-seed systems, input and service provision, marketing (see below), and knowledge sharing are also shaping the future of wheat.

Markets and value chains. During the past few decades, developing countries as a whole have gradually become major net wheat importers, and wheat now accounts for 43% of food imports in developing countries. While the demand for wheat for human consumption in developing countries is expected to grow at 2.6% per annum until 2020, the growth in demand for feed wheat is predicted to grow at 5.0% per annum.

A dramatic growth in demand for certain high value end-uses including flour, pasta, and bakery products is expected. In addition, wheat produced in a small number of European countries may be increasingly used for biofuel production. Consequently, wheat value chains will become increasingly differentiated, and food quality attributes will assume greater importance. Clearly, research and breeding efforts must be ready to serve these evolving and diversifying demands. On the supply side, with the continued rise in international oil prices, the costs of production inputs, especially fuel and nitrogen (N) fertilizer, are also increasing, thereby decreasing the incentives for the adoption of new input-responsive cultivars (see Figure 6). Due to the increased price of N fertilizers, as well as growing environmental concerns about water and air pollution from N fertilizer use, breeding for nutrient use efficiency will become a high priority in wheat improvement. Similar dynamics are expected around the use of irrigation, and thus the need for an increasing emphasis on drought tolerance and water use efficiency by wheat improvement programs.

Policies and institutions. Government policies and institutions shield many producers from international market effects. In many countries, the incentives for the adoption of new varieties and technologies are distorted by subsidies and trade measures. For example, farm gate prices in 2005 varied from around US\$ 110 per ton in Kazakhstan to US\$ 150 per ton in Australia (large, exporting rainfed producers) to US\$ 301 per ton in Saudi Arabia.¹⁰

Knowledge and capacity. The improvement of databases for use in priority setting offers the means to increase payoffs through optimizing investments in wheat research and breeding, and crop management research. Global wheat mega-environments have been delineated that distinguish abiotic adaptation and biotic stress resistance combinations required for different types of wheat (Trethowan et al. 2005). There is growing recognition of the importance of socioeconomic factors as determinants of the adoption and productivity of new agricultural technologies (Lee 2005). Thus, mega-environments must be further refined to reflect these socioeconomic factors. As spatial data availability and analytical power grow, geographic information systems (GIS) offer a viable platform to combine biophysical and socioeconomic information for priority setting, such as in the FAO-World Bank farming systems classification of Dixon et al. (2001). Using such a framework at global or national levels, together with spatial

¹⁰ Domestic wheat prices are also substantially above world prices in the EU and especially Switzerland.

knowledge bases of livelihoods and production constraints, wheat research for development (R4D) can be systematically targeted to specific regions and farmer groups.

Farmers also benefit from improved knowledge of wheat varieties, production practices, and markets, consistent with the spreading “production management” revolution in small-holder farming.

Agricultural resources. Environmental concerns, stagnating yields in many wheat-based systems, declining soil fertility, and global climate change are all factors that will have major impact on the wheat industry over the next two decades. While a major portion of the wheat in large developing countries is produced under irrigation, major exporters (North America, Argentina, Australia, Europe, and Kazakhstan) produce wheat under rainfed conditions mostly in low-cost production systems. Pimentel (1997) calculated that to produce 1 kg of grain, wheat needs on average 900 liters of water as compared to 1400 liters for maize and 1900 liters for rice. Wheat is, therefore, the most water use efficient (WUE) of the three major global cereal commodities. However, the variation for WUE within crops is extremely high. In wheat it varies from 700 L of water to produce 1 kg grain in the most efficient rainfed or irrigated systems to 5000 L for 1 kg grain in very inefficient irrigated systems (Molden 2007). Agriculture in Asia uses 85% of all fresh water, in Africa 88%, and worldwide 70% (World Resources 1998-99, IWMI 2007). Considering the increasing water scarcity, it is likely that irrigation water will be used more and more for high value crops, and wheat will be grown in more extensive systems. Climate change may well be one of the most important of a series of global changes that will shape wheat production and consumption in the future (see Hodson and White, this volume).

Possible futures: 2020 and 2030

The development of global and regional future scenarios for wheat production has been based on the “wheat drivers” discussed above, combined with projections derived from economic modeling by IFPRI (Rosegrant et al. 2001, Rosegrant et al. 2007), FAO (Bruinsma 2002, FAO 2006), OECD-FAO (OECD-FAO 2007), and the University of Iowa (FAPRI 2007), supplemented by expert assessments from other sources (e.g., GRDC 2004). In the following discussion, pressures that enhance wheat production are referred to as “facilitators,” and those that tend to hold back production increases are termed “dampeners.”

The demand for wheat is projected to continue to grow, albeit at a declining rate. The wheat 2020 global production forecast is 760 million tons (implying 1.6% annual growth), equivalent to 29% of total global cereal demand (slightly down from the current share of 30%), equivalent to 74.3 kg cap⁻¹ yr⁻¹. Consumption in the developed world is expected to be 103.8 kg cap⁻¹ yr⁻¹, compared with 67.7 kg cap⁻¹ yr⁻¹ in the developing world (Rosegrant 2001). These forecasts suggest that most wheat in developing countries will continue to be consumed as food, while in developed countries a significant portion will be used as animal feed.

Great regional variation exists in per capita consumption of wheat, varying from virtually zero in some African countries to 200 kg cap⁻¹ yr⁻¹ in countries in North Africa, and Central and West Asia. Global average yields will need to increase to 3.5 tons ha⁻¹ (up from the present 2.9 tons ha⁻¹) if the expected global wheat demand in 2020 is to be met. Taking into consideration the growing scarcity of land and water, the increasing demand for high value products, and climate change, it is likely that a greater proportion of wheat will be grown in extensive rainfed systems, such as currently predominate in the Southern Cone of South America and Central Asia.

Further development of institutions can be expected, with a stronger role for the private sector in seed systems across many regions. As a consequence of better seed systems and improved farm management, there will be faster turnover of varieties. As labor costs rise, the average size of operational holdings (not necessarily ownership) will increase, which will foster a greater degree of mechanization and other economies of scale. With improved agronomic management, a growing proportion of wheat is likely to be produced under conservation agriculture systems. With improved varieties better tailored to new crop management practices, increases in input use efficiency should facilitate a reduction in the level of input applications while at the same time maintaining or increasing yield (as compared to present rainfed conditions). This should result in significant net profits for wheat producers. In addition, the development of markets for different end uses will require more segregation of wheat types.

Projections of the future of wheat production suffer from two main sources of variability (Rosegrant 2001): global and macro-economic uncertainties plus specific “dampeners” and “facilitators” that affect wheat productivity (summarized in Figure 10).

The most probable set of forecasts indicate that wheat production (and consumption) will grow at approximately 1.6% per year, with the consequence that 760 million tons will be produced in 2020 and approximately 813 million tons in 2030. The required growth could be derived from a number of sources, some historical (as described above) and some new (discussed below). The set of key facilitators that will tend to strengthen productivity (and production, on the assumption that area would not increase) is identified, as is the set of key dampeners that will tend to depress productivity and production. The facilitators include “synthetic” wheat; biofuel demand (although this might also increase competition for resources and dampen growth); better management of genotype x system interactions; increased breeding efficiency through MAS, etc.; hybrid or GM wheat; increasing private sector investment; and the growing demand for health foods and, ultimately, for special uses such as cosmetics and emerging industrial uses. On the other side, dampeners include shortage of fresh water for irrigation; soil degradation; emerging biotic stresses; high energy prices; failure to increase yield potential; shift of a substantial proportion of the wheat production area from intensive irrigated to extensive rainfed production; and climate change with respect to the negative effects of heat stress, insufficient irrigation water availability, and increased pest and disease pressure (although climate change may also lead to the expansion of wheat into new rainfed production areas).

Overview of Threats and Opportunities for Future Increases in Wheat Productivity

Within the framework of the expanding and changing wheat markets, the reduced availability of land and water resources, and the evolution of institutions and scientific knowledge (discussed above), there are a number of significant threats as well as opportunities for wheat productivity increases and poverty reduction in the short term and for income and livelihoods improvement in the longer term. Before discussing threats and opportunities in the following sub-sections, we will briefly examine two factors, climate change and biofuels production, which may present both threats and opportunities to producers in different regions of the world.

Adapting to the effects of climate change

While wheat has gained from increased levels of CO₂ in the atmosphere, it is sensitive to high temperature, especially at anthesis, although the effects depend on variety, management, and environmental factors (see Hodson and White, this volume). There are threats to major wheat

producing areas such as the Indo-Gangetic Plains unless varieties with greater tolerance to heat stress are released. In contrast, there will also be some areas that gain from climate change, through expansion of the area suitable for wheat production and increased yields, such as in Kazakhstan, Siberia, USA, Canada, and other areas at northern latitudes, due to a longer growing season plus warmer and wetter growing conditions. Climate change may also alter other environmental factors and risks that can affect wheat production, e.g., flooding, lower light intensities, pests, and diseases. Of course, such environmental changes may affect high value crops even more than wheat. Nevertheless, the main challenge for wheat breeders at this stage is selecting genotypes able to tolerate heat stress and water deficits.

Biofuel production

Although wheat grain is not currently used to any great degree as a feedstock for bioethanol production in developing countries, the strong demand for maize grain for bioethanol production, especially in the USA, has contributed to the substitution of maize for wheat, which has aggravated the market effects and resulted in substantial increases in the price of wheat (Dixon and Li 2007). This has generated immediate benefits for farmers producing a surplus of wheat for sale. However, in the medium to long term, wheat may lose competitiveness compared to bioenergy crops such as maize. Furthermore, the removal of large volumes of straw from wheat fields for “second generation” bioethanol production based on the fermentation of cellulose will accelerate soil degradation.

Countering threats to wheat productivity

Counteracting stagnating gains in grain yields. Stagnating yield growth has become a concern for major wheat producing regions worldwide (see Reynolds et al. 2007 and Nagarajan 2005). However, since the underlying reasons for this stagnation are highly complex, the solutions are not likely to be straightforward. Investments in wheat breeding have declined in absolute terms along with the general reduction in agricultural research funding (Pardey 2006). Furthermore, the impact of non-sustainable agronomic practices and consequent declining soil fertility and decreasing response to inputs is channeling more and more breeding efforts and wheat improvement resources in LDCs (less developed countries) towards traits related to declining soil fertility (e.g., tolerance to micro-nutrient deficiency, tolerance to soil-borne diseases, tolerance to drought and salinity). Farmers cannot, therefore, utilize the increased yield potential

of improved varieties and technologies, and their net income may even decline, as more inputs are applied to compensate for declining soil fertility (Sayre 2004). A concerted effort by farmers, agronomists, breeders, and policy makers is needed to improve soil fertility and input use efficiency through sustainable and low-cost practices, so that the higher yield potential of improved cultivars can be exploited in all production environments and provide farmers with a stronger incentive to replace old cultivars.

The role of maintenance breeding. The importance of maintenance research to the wheat industry is widely recognized: maintenance research usually generates high economic returns (through protecting against production losses) and will be increasingly required to defend past yield gains. A study of the value of durable multigenic resistance to leaf rust in developing countries estimated its net present value at US\$ 5.36 billion, with a benefit-cost ratio of 27:1 (Marasas et al. 2004). The wide adaptation and yield stability of cultivars derived from CIMMYT materials are the result of long-term investments and breeding for disease resistance. However, disease resistant varieties need to be replaced over time, as new races of a particular disease overcome the genetic resistance. The latest example of this is the occurrence of Ug 99, a new race of stem rust (see Box 4). Without investment in maintenance research and breeding, global production is threatened (World Bank 2007). Around half of CIMMYT's investments in wheat are focused on maintenance research and breeding, in particular related to rust resistance. This is not unusually high, as generally a third to a half of current crop breeding R&D is invested in maintenance activities, leaving reduced resources to address advances in productivity (World Bank 2007).

Today, most of CIMMYT's advanced lines targeted for irrigated areas carry four to five minor genes for leaf and yellow rust resistance. This has surely contributed to the lack, in recent decades, of severe leaf rust epidemics in areas where CIMMYT-derived germplasm is grown. As one of the highest priorities for the coming decade, CIMMYT has made a firm commitment to build minor-gene-based (durable) resistance to all three cereal rusts into its germplasm.

Box 4. From Complacency to Crisis: Stem Rust Race Ug 99

Stem rust (*Puccinia graminis*) is 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 named Ug99) and now threatens 120 million tons, or 20%, of the world's wheat in Central and North 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 1953-54 and caused a 40% loss in spring wheat yields that would be worth \$1 billion or more today; this led to the establishment of a response system comprising a) a robust collaborative international network of wheat improvement institutions, germplasm sharing, and strong human capacity and infrastructure dedicated to stem rust research; b) increasing frequency of resistant cultivar releases. As a result, there have been no stem rust pandemics over the last five decades. Unfortunately, over the years this response system has atrophied; consequently, the emergence and spread of Ug 99 represents a major threat to global wheat production.

A concerted emergency global research effort under the umbrella of CIMMYT and ICARDA has been established: the Global Rust Initiative (GRI) (www.globalrust.org), initiated by Dr. Norman E. Borlaug in 2005. More than 20,000 wheat accessions, including major cultivars, have now been evaluated in Kenya and Ethiopia, and results indicate that as many as 90% of the world's commercial wheat varieties are susceptible. Fortunately, new resistant high-yielding wheat lines have also been identified and are now being distributed globally.

The message 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. The system would allow scientists to anticipate outbreaks and give early warning to farmers, who could then take preventive measures such as fungicide applications.

Evolving and emerging biological threats. Weeds, insects, and diseases reduce actual world wheat production by an estimated 28% (Oerke 2006), and the loss could be as high as 50% without effective plant protection.¹¹ Over one-third of losses from these biotic constraints are caused by fungal diseases (equivalent to US\$ 15 billion at 2007 international prices), and most of

¹¹ Although 50% total losses may sound high, crop losses without application of plant protectives are lowest for wheat among major crops and can reach up to 80% for cotton—which explains why chemical application in cotton is so high and why GM cotton became popular so fast with growers.

that is due to the three rusts of wheat (see Box 4), although the single largest cause of losses is weed competition (equivalent to US\$ 12 billion at 2007 international prices). Better control of these biotic constraints would add resiliency to world food production and, therefore, world food, livelihood, and geopolitical security.

Though actual production losses are already high, it is anticipated that they will rise due to increased abiotic stresses caused by global climate change; however, diseases and pests may also become significant constraints in regions where they have not been observed before or were not previously economically important.

The potential of new threats is exemplified by wheat blast, caused by *Magnaporthe grisea*, which in 1986 was reported for the first time on wheat, in-situ, in Paraná, Brazil (Igarashi et al. 1986). It most likely adapted to wheat from its original colonization of the weed *Digitaria insularis* (Urashima et al. 2005). Within a few years, it spread to major wheat growing areas of Brazil, Bolivia, and Paraguay, and became a limiting factor on more than 3 m ha in the region. In the Bolivian lowlands, wheat blast led to a 50% decline in the area sown to wheat (Condori, pers. com., 2007). Though tolerance was found in wheat by EMBRAPA (Brazil) researchers, the majority of germplasm tested proved to be susceptible. The potential threat of wheat blast cannot be overstated; the disease represents a serious risk to wheat production and food security should it spread to neighboring Argentina and more dramatically if it spread to Asia, which is feasible since seed transmission has been reported. Once its epidemiology is better understood, spatial modeling could identify areas of potential risk. With the effect of climate change on pest and disease populations, situations such as this are likely to be increasingly common.

Bearchell et al. (2005) conducted a study using samples collected over 160 years and kept in UK Rothamsted archives. Results showed that the ratio of *Phaeosphaeria nodorum* and *Mycosphaerella graminicola* is strongly correlated with changes in atmospheric pollution, as measured by CO₂ emissions. This illustrates that long-term, economically important changes in pathogen populations can be influenced by anthropogenically-induced environmental changes, of which CO₂ concentration and temperature are major components (see Hodson and White, this volume).

The potential expansion of wheat growing areas in northern latitudes due to global warming, expansion of zero and minimum tillage, diversification of crop rotations, and changes in sowing and harvest times to fit wheat into more complex rotations will undoubtedly be accompanied by changes in the disease and pest spectrum. Thus effective monitoring systems are required to cope with the new and old challenges to wheat production posed by diseases and pests.

Threats to food safety and international trade. Scab, or *Fusarium* head blight, adversely affects wheat grain size and yield, but it is the associated mycotoxin contamination that most jeopardizes trade, as it can cause serious health problems in humans and animals (see Meng et al., this volume). *Fusarium* fungi are highly prevalent on cereals grown in the temperate regions of the Americas, Europe, and Asia (European Commission 2002). Due to the global importance of this problem, CIMMYT has created a Global Fusarium Initiative to provide a platform for international collaboration on *Fusarium* research by facilitating the sharing of knowledge and genetically enhanced wheat germplasm as well as other breeding materials and tools. Various sources of resistance are being tagged with DNA markers for use in rapid introgression and pyramiding of distinct types of resistance against this pathogen and/or its production of mycotoxins. Research efforts on pathology screening methods, coupled with advances in germplasm enhancement, should lead to the development of new genotypes with novel and durable sources of resistance. In addition, a holistic fight against mycotoxins is envisaged, with a focus on integrated crop management (including the use of genetically enhanced cultivars), low-cost detection technology, and a participatory assessment process to ensure food safety and to overcome potential trade barriers for the export of grains from the developing world. Genetically modified wheat resistant to *Fusarium* (and, thus, with low mycotoxin content) has been developed, but not yet released for commercial production.

Falling investments in wheat research. Most wheat research in developing countries is currently conducted by public institutions, a situation similar to that of rice and sorghum, among the major global field crops. This is in contrast to other commodities such as maize, soybeans, rapeseed, and cotton, where the private sector is the major driver. Hybrid technologies have been the principal mechanism for safeguarding private sector investments, although more recently patented transgenes or entire transgenic plants have provided even greater protection in countries with reliable legal systems. In the absence of hybrids and GM technologies, there is a need for

royalty or other value capture or incentive systems to increase private sector investments in wheat improvement (Pardey 2006). The biological protection provided by the hybrid variety system, which requires farmers to buy seed for every season, is clearly a massive incentive for private investment. The private sector, including multinationals, make huge investments to develop and apply new breeding and production technologies in maize, soybean, and cotton, e.g. in the area of genomics, transgenics, informatics, and molecular breeding. Most of these technological advances are protected by patents, providing an even stronger investment protection system in OECD and emerging economies.

Funds for wheat research, in particular in LDC, are derived mostly from public donors and often spread over many research programs, making each investment relatively small and often less efficient. Average aggregate yield increases in the USA during the 1990s rose 15.5% for maize but only 6.3% for wheat (National Association of Wheat Growers et al. 2006), although the lower productivity of wheat growing areas compared to those for maize should be noted. Similar trends are observed in the LDCs. Moreover, Pardey (2004) showed that public agricultural R&D spending declined from 7% annual growth (not clear what the basis is for percent increase) for the period 1976-81 to below 4% for the period 1991-96. In 2000, in developed countries the public and private sector each invested approximately US\$ 10 billion and US\$ 12 billion annually, respectively, while in developing countries the public sector invested approximately US\$ 13 billion but the private sector less than US\$ 1 billion (Pardey et al. 2006). When measured as a proportion of agricultural GDP, R&D spending in developed countries almost doubled, from 1.4% to 2.4% during the two decades from 1981 to 2000, whereas the relative level of spending in developing countries stagnated at around 0.53% (Pardey et al. 2006). While a strong public sector working cooperatively with the private sector is essential to ensure benefits from the gene revolution (Pingali and Raney 2005), the key challenge is to attract private sector investment in agricultural research in developing countries. The commercial seed sector depends upon profitable development and sale of seed, i.e., they must be able to rely on a reasonable return on their investments. Thus, a major challenge in the coming decades is the development of technologies or mechanisms that can synergize private sector investment in wheat breeding across the world.

Lack of diversity in farmers' fields. Every year hundreds of elite wheat lines are tested by NARSs, but only a very few are used directly or indirectly in the release of new cultivars. Moreover, there has been a trend in every agro-ecological region for a small proportion of released cultivars to dominate production. These mega-varieties then cover millions of hectares, often spread over many countries or even continents, increasing the risk of large epidemics, if their disease resistance breaks down. In recent years, participatory variety selection has been employed in various regions to increase the diversity in farmers' fields. However, such an approach has to be complemented by strong breeding programs assuring adequate genetic diversity for disease resistance. We anticipate that, until such time as various wheat grain qualities are differentiated in the market place, mega-varieties will continue to emerge. Meanwhile, the most effective approach to deal with the threat of international pandemics due to homogeneous production is to develop cultivars whose resistance is based on race non-specific genes and, consequently, more likely to be durable.

Wheat genetic diversity in breeders' populations. The genetic diversity among CIMMYT lines fell during the Green Revolution period, but was largely recovered over the last two decades (reviewed by Reynolds and Borlaug 2006a). The development and use of "synthetic wheat" lines in CIMMYT breeding programs have provided important new sources of genetic diversity for water use efficiency and biotic stress tolerance. These materials are now being used by NARSs for the development of new cultivars (Sichuan Academy of Agricultural Sciences, China ref.). To provide NARSs with new and diverse sources of important traits in good agronomic backgrounds is a prime objective for wheat improvement at CIMMYT and is therefore addressed in more detail in the chapter by Crouch et al., this volume.

Seizing opportunities for increasing wheat productivity

Genetically modified wheat. The first reports of the successful transformation of wheat appeared in the early 1990s. Contained evaluation trials of transgenic wheat lines with a wide range of enhanced or novel traits have been approved in several countries. However, political, social, and commercial issues have blocked any of these prospective new wheats from being approved for commercial production. This is in dramatic contrast to the progress in many other major crops (notably maize, soybean, cotton, and canola) that now account for more than 100

million ha of commercial transgenic crop production across 22 countries (James 2006). Transgenic cultivars have significantly reduced production costs, as well as contributed to increases in average yields for these crops, leading to an estimated increase in farm income of more than US\$ 25 billion. The GM approach would be particularly valuable for traits for which there is limited or no genetic variation within the *Triticum* species. This would include herbicide resistance, *Fusarium* resistance, novel quality traits, and technologies for creating hybrid cultivars. In addition, GM technologies hold promise for enhancing drought and heat tolerance, as well as disease and pest resistance.

There have been substantial commercial concerns regarding the effect of consumer resistance to GM products in some countries. However, more recently there has been a resurgence of interest in GM wheat, and it is very likely that GM wheat cultivars will be released within the next ten years. It is worth noting that wheat has already benefited from GM traits in other crops in the rotation, e.g., herbicide resistant soybean in Argentina has helped reduce weeds in wheat crops grown in the same rotation. It is expected that consumers will be more likely to accept GM wheat if the improved traits have a significant effect on product quality, e.g., increased nutrient concentration, food safety (free from toxins), and pharmaceutical and other health benefits. This will clearly require efficient segregation systems (along the supply chain) and labeling systems (at the commercialization point), plus reliable intellectual property rights and royalty collection systems that are not currently in place in many major wheat growing countries.

Hybrid wheat. Picket and Galwey (1997) evaluated 40 years of attempts to generate hybrid wheat cultivars and concluded that hybrid wheat production is not economically feasible because: a) limited heterotic advantage: historically only about a 10% advantage is commonly found, though introducing new genetic diversity (e.g., through synthetics) may increase heterosis; b) lack of advantage in terms of agronomic, quality, or disease resistance traits; c) seed production costs higher than heterotic yield advantage; and, probably most importantly, d) heterosis can be "fixed" and consequently hybrids would have no biological advantage over inbred lines. This is reflected in the small investments in hybrid wheat development globally as of 2007, as well as the small acreage under hybrid wheat. Functioning royalty collection systems in most OECD countries may also have reduced the incentives for breeding companies to produce hybrid wheat seeds.

Though biotechnological methods now allow the capture of increased heterosis by direct selection of favorable alleles and new genetically based systems to control male sterility, which are not based on CMS[i], that also may reduce the costs of commercial hybrid seed production, it remains to be seen whether hybrid wheat production will generate more interest in the future, in particular when functioning royalty collection systems are in place. If GM wheat is accepted, hybrid wheat may become economically viable. On the other side, increasing knowledge of the wheat genome and subsequent gene discovery will make MAS more efficient and more important, since new improved wheat cultivars will be developed more efficiently and faster. Considering the currently limited heterosis, high seed production costs, and the limited global investments in hybrid wheat on one side, and on the other side emerging options from biotechnology, we refrain making a prediction about the future of hybrid wheat, but tend towards a slightly pessimistic view for chances of hybrid wheat over the next two decades.

Wheat quality. As analyzed by Meng et al. (this volume), consumer preferences are evolving with increasing incomes, and the demands for specific quality attributes are changing. The industrialization of wheat processing that has occurred for bread will also take place for other products, including chapatis. This will result in increased demand for specific and consistent qualities of wheat. The differentiation of wheat products, whether by visible or indirect characteristics, opens the possibility of adding value to the wheat industry, creating extra employment along value chains, and increasing farm gate prices. This, in turn, may improve incentives for farmers to adopt new varieties with enhanced grain quality characteristics (supported by the necessary crop management practices). This presents a major challenge for wheat breeders to develop new varieties with stable novel quality profiles (irrespective of stresses during cultivation) while maintaining adequate yield potential.

One universal quality trait is the nutritional value of wheat. The Harvest Plus (H+) Challenge Program is attempting to introgress genes for high micronutrient grain content—in particular iron (Fe) and zinc (Zn)—into diverse germplasm. High micronutrient grain content and high micronutrient bio-availability will become essential traits of CIMMYT's wheat germplasm. It

may be difficult to improve micronutrient content while maintaining yield potential using natural genetic variation without GM technologies. The increasing demand for wheat with specific quality characteristics raises the issue of whether the International Wheat Improvement Network should allocate significant resources to develop intermediate products with the necessary quality traits or alternatively focus on strategic traits with more widespread relevance, such as increasing and protecting yield potential and improving drought and heat tolerance. For the foreseeable future, weak infrastructure and institutions may hamper segregation for added-value wheat quality products in the supply chain in many developing countries. However, there are certain core quality characteristics that should be maintained by international breeding programs, and CIMMYT will focus on these (Meng et al., this volume). In contrast, NARS breeding programs may be in a better position to introgress specialty quality traits into locally grown cultivars to meet the needs of the local wheat processing industry or satisfy specific export criteria. Of course, wherever possible, the CIMMYT gene bank will identify accessions containing potentially valuable diversity for various quality traits and provide this germplasm to interested public or private partners.

Water use efficiency, and drought and heat tolerance. The adoption rates of the early semidwarf cultivars were significantly higher in high-input environments. However, the cultivars performed less well in marginal cropping systems, and thus farmers, being more risk adverse in these areas, tended to retain their traditional cultivars (Byerlee 1994). Though the genetic basis of drought tolerance in wheat is complex and difficult to improve, substantial genetic progress has been made (Reynolds and Borlaug 2006b, and Box 5), and now many drier environments report significant adoption of improved varieties (over 60% in drought-prone areas in LDC) and improvements in productivity over time (Trethowan et al. 2002; Lantican et al. 2002; Evenson and Gollin 2003a). Wheat is among the three major cereals that use water most efficiently, which is also reflected in the fact that most wheat exporting countries produce wheat under rainfed conditions. As noted above, with water becoming a major limitation for crop production in many regions, wheat will increasingly be grown in rainfed areas. Therefore, drought tolerance in wheat will remain among the highest priorities of international wheat improvement at CIMMYT.

Box 5. Irrigated Wheat Also Needs Drought Tolerance

More than 80% of all fresh water is used for agriculture, and slightly more than 80% of irrigated wheat is grown in less developed countries. Water scarcity and rapidly declining ground water tables increasingly force farmers to reduce the number of irrigations and apply supplementary rather than full irrigation (Rosegrant et al. 2002). It is also likely that in the future more countries will charge farmers for water use. The risk of irrigated wheat being exposed to temporary drought is consequently increasing. CIMMYT therefore emphasizes the development of cultivars that combine high yield potential with tolerance to severe drought even at very low yield levels. Before being distributed to NARSs, elite wheat lines are evaluated for their water use efficiency in fully irrigated as well as drought stressed trials to ensure that wheat cultivars targeted for irrigated areas can cope with temporary drought periods.

Cropping systems management and conservation agriculture. As discussed by Sayre and Govaerts (this volume), maintaining and expanding wheat production is critically dependent on land and water resources that are being degraded in many irrigated and marginal wheat producing areas. Evenson and Gollin (2003a) estimated that one-third of the increase in food production in Asia between 1961 and 1981 (the main Green Revolution period) was attributable to crop improvement; the other two-thirds arose from a variety of crop management and institutional factors, in particular increased fertilizer use and better weed control, water management, and market access. Furthermore, there is scope for exploiting the positive interactions between genotype and cropping systems management (G x S). One of the proven crop management routes for improving the productivity of sustainable agriculture is the application of conservation agriculture systems (including reduced tillage, which saves resources, slashes costs, reduces greenhouse gases, and stabilizes production), while creating the management conditions for the expression of a greater proportion of genetic yield potential than in degraded, infertile conditions (Ekboir 2002). Key elements of such an approach include effective weed control, using herbicides as appropriate, and soil fertility management. Thus, without improved and profitable crop management, the full benefits of improved wheat germplasm will not be realized.

Enabling policies for integrated resource management, crop improvement, and agricultural institutions. Some high potential wheat producing areas with good market access and strong supporting agricultural services, such as western parts of the Indo-Gangetic Plains, have witnessed rapid yield growth and, at the same time, diversification away from cereals

(Erenstein, this volume; Chand 2005). Often, intensification of food crop production systems encourages diversification to higher value crops, which augments rural livelihoods, reduces farmer poverty, and stimulates off-farm economic growth, local rural job creation, and rural poverty alleviation (Dixon et al. 2007). In some circumstances, increased wheat productivity might even lead, through the pathway of intensification, diversification, and income growth, some farmers to eventually stop producing wheat and even to leave agriculture all together. With such poverty reduction pathways and linkages in mind, wheat improvement, resource and cropping system management, value chain development, and policy adjustment should be harmonized and ideally planned and implemented in an integrated fashion to promote sustainable wheat-based farming systems. Within the context of choices open to farmers, the specific outcomes for national food security and wheat-based farming systems from agricultural and rural policies will depend on the particular combinations of resource policies (e.g., land and water regulations and pricing), agricultural market policies (e.g., seed, fertilizer, and machinery subsidies), and grain procurement, subsidies, and consumer policies (e.g., food price controls and subsidies).

Access to data, information, and knowledge. Policy makers, researchers, and farmers generally depend on different types of information from different sources. Recent advances in information and communication technologies are enabling the creation of knowledge platforms. These platforms (e.g., the International Crop Information System [ICIS],¹² the IWIN website,¹³ and the Cereal Knowledge Bank¹⁴) can become a very powerful tool for scientists, extension specialists, farmers, and policymakers. To give a few examples, scientists developing new wheat varieties need to have access to data from genomics laboratories linked with phenotypic data collected from field trials in various environments representative of key target regions. Farmers will often benefit as a result of extension systems having faster access to new information and technologies from laboratory and experimental fields, which will allow them to make more efficient and sustainable decisions at the farm level (CIMMYT 2006). Similarly, policymakers and farmers need to have access to up-to-date global and local market information and prices to better guide their decision-making processes, such as e-Chopal, the electronic market information system in

¹² Website address.

¹³ Website address.

¹⁴ Website address.

northern India. On-line tools for monitoring the epidemiological situation of pests and diseases will also be greatly beneficial to all.¹⁵ To address global challenges in wheat science and production, the exchange of both wheat genetic material and the associated knowledge through existing networks and new partnerships (e.g., IWIN) will be a critically important international public good (IPG) that must remain freely available to all if it is to achieve its full impact.

Emerging uses for wheat. Few observers are aware of the speed with which new uses are being developed for cereal grains. Following a recent assessment by GRDC (2004), the projected growth in Australian wheat exports as a consequence of these new uses exceeds by far the growth in domestic demand. For example, the projected growth in industrial uses for starch, bioplastics, and high molecular weight ingredients is enormous—as much as 45% of Australian wheat exports by 2020 may be destined for advanced industrial uses (GRDC 2004). A second use, “first generation” bioethanol production from grain and “second generation” bioethanol production from cellulose in biomass, including straw, is emerging. This is driven by growing energy demands, especially for transportation, and by finite fossil fuel reserves. New foods such as low carb wheat or non-allergenic (low glycemic index) wheat also represent substantial potential niche markets, as do new uses for animal feed. Finally, potential nutri- or agricultural and cosmetic uses of wheat are also under discussion, though these may not become major markets for wheat for many years. Naturally, the increasing diversity of uses is a major challenge for breeders and crop management researchers, as many of these niche market targets will require specifically tailored breeding programs in producer countries. Some of the additional income from supplying niche markets will accrue to farmers, and it is unlikely that the poor will suffer higher food prices because the small production volumes are unlikely to significantly affect wheat markets or prices.

Implications for International and National Wheat Research

Historically, wheat production has made a major contribution to global food security for millennia. Given the steady increases in wheat productivity during the past 40 years underpinned by better varieties, improved crop management, inputs, and markets, wheat has continued to play a major role in global food security and poverty reduction. Today wheat contributes around one-

¹⁵ GRI website address.

quarter of the global human consumption of calories, for which there are no easy substitutes in many major wheat consuming countries. The economic returns to productivity enhancing wheat research have been consistently high, as have the returns to maintenance research to defend those gains against a dynamic profile of environmental and biotic stresses.

Managers of wheat research in the first quarter of the 21st century confront a completely new context of slowing wheat productivity, growing demand for biofuels, strong productivity growth in competing food and cash crops, changing agricultural markets and prices, evolving input and service institutions, and climate change. The analysis of wheat systems improvement over the next two decades can be framed around factors that either strengthen or diminish the growth of wheat productivity and production along the annual 1.6% growth required to meet expected demand in 2020. While production expanded strongly during the three decades preceding 1994, the rate of expansion declined during the period 1995-2006—as with most other major crops. Some of the constraining factors include declining soil fertility and water tables, growing biotic stresses, higher energy and input prices, stronger cost-price squeeze on farmers, and weaker incentives for varietal replacement, against a backdrop of low grain prices and diminishing research investments. Conversely, there are a number of positive factors that could strengthen growth and accelerate productivity gains, including synthetic wheats, effective management of genotype x system management interactions, and increased breeding efficiency with molecular tools, as well as higher real prices, competition from biofuels, and new markets for wheat-based health foods, cosmetics, and new industrial uses. Three major factors have potential accelerating or constraining effects: biofuels, climate change, plus food safety and identity preserved production.

All major current wheat exporters (USA, Canada, Argentina, Australia, Europe, and Kazakhstan) produce wheat in competitive, generally low-cost rainfed systems. Wheat is among the most water use efficient of the major staple crops, and we predict a shift of wheat production away from well-irrigated intensive systems towards more extensive systems with either supplementary or no irrigation. With high energy and input prices, increasing wage rates, and growing demand from other sectors for resources and environmental services, farmers are caught in a cost-price squeeze that favors cost-saving varietal traits such as resistance to biotic and abiotic stresses;

production cost-saving practices such as conservation agriculture; and crop trait/production practice combinations, including rotations, that enhance water and nitrogen use efficiency.

In the search for pathways through which wheat research may impact poverty reduction, the primary challenges in the coming decades include: maintaining the effective international wheat improvement network and the willingness of its participants to share germplasm, data, and knowledge; exploiting genetic variation and wider application of new tools for efficient breeding; improving yield potential, grain quality, and input use efficiency, especially for agroclimatically and socioeconomically marginal areas where wheat might expand in the future; continuing maintenance research to defend past gains against pests and diseases such as stem rust race Ug99 and *Fusarium*; promoting sustainable cropping systems, which transform genetic potential into farmers' yields and maintain a productive agricultural resource base; facilitating knowledge sharing, which empowers NARSs and farmers; and enabling value chains, institutions, and policies that foster efficiency-enhancing incentives for farmers, input suppliers, and processors. Although these challenges are interdependent and the goals synergistic, international wheat research will focus on the production of IPGs with strong potential for spillovers across farming systems and regions. Nevertheless, it is necessary to take into account complex resource, farming, institutional, and corporate systems, as well as alternative uses of water, land, and labor resources in agriculture and industry, the growing food safety movement, and corporate-led transformation of value chains.

Wheat quality will grow in importance in developing countries from nutritional and market perspectives, which will require increasing attention from breeders, agronomists, and value chain analysts. For the foreseeable future, the bulk of wheat will be consumed in LDC as traditional products, i.e., principally as a low cost staple. However, even for traditional products the industrialization of processing will add new demands for quality characteristics, as well as consistency in quality. Moreover, the growing purchasing power of middle-class urban consumers will create new markets for higher value wheat products with an additional set of local quality characteristics. There are major new end-uses for wheat that will add to the industrial value of wheat and increase the demand for high quality wheat requiring crop, management, and value chain improvement. The International Wheat Improvement Network will need to incorporate an “international” set of core qualities (e.g., protein concentration, dough

elasticity, kernel hardness, and color), while NARSs will have the challenge of addressing additional quality requirements for national niche markets.

Quality traits are only one area where valuable genetic variation will be sought from genetic resources. Management and screening of germplasm accessions are likely to remain in the public arena. However, a growing role for the private sector in molecular breeding and wheat research in developing countries is anticipated. Largely spin-offs from public sector research, new tools available from molecular research are expected to enhance the efficiency with which wheat scientists can transfer genes from alien species into bread wheat or durum wheat and, in turn, the efficiency with which breeders can incorporate those new genes and alleles into their mainstream breeding programs. In this connection, synthetic wheat lines offer scientists an important new breeding resource for increasing yields as well as enhancing biotic and abiotic stress resistance.

Climate change is a challenge for wheat scientists, who will have to deal with more frequent and extreme heat and drought stress, growing biotic pressure, and increased climatic volatility. There will be winners and losers from climate change: while production in the sub-tropics will come under increasing stress, large areas in the high northern latitudes will become moister and warmer and thereby suitable for extensive wheat production.

If cropping systems management research does not identify productive and sustainable farming systems that can be readily adopted by resource-poor farmers, then breeders will need to invest more and more effort into improving traits to solve problems related to declining soil fertility and water availability. This would divert resources from crop improvement for other economically important traits such as tolerance to biotic and abiotic stresses, grain yield, and quality.

Moreover, there is a general failure to recognize the new generation of global challenges to systems agronomy related to achieving the potential of new wheat cultivars to increase input and water use efficiency, boost food production, and meet food safety standards in the new context referred to above. Research directed towards the generation of widely applicable systems management solutions will be best served by strengthening an international advanced strategic science platform, such as managed by CIMMYT in Mexico, linked to cropping systems research hubs in globally important farming systems (such as the Rice-Wheat Consortium in South Asia or the collaborative research on maize-wheat systems in China and cotton-wheat systems in

Central Asia) with an initial focus on increased input efficiency, in particular WUE and nutrient use efficiency (NUE), crop residue management, and adaptation to climate change.

As international wheat improvement generates improved germplasm and system management technologies, it will be necessary to integrate resource and crop management, improved germplasm, and policies at the national level. The achievements of the Rice-Wheat Consortium in South Asia is one example of how this could be achieved (Seth et al. 2003). The increasing current and projected real prices of wheat threaten the historical achievements of wheat research in reducing food prices and poverty. Increased wheat research-generated productivity enhancements, through expanded investment in wheat research and the collaboration of NARSs and CIMMYT, can ameliorate such food price increases and develop sustainable solutions to protect the environment, maintain food security, and reduce poverty.

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Table 1. Area and productivity of wheat in selected regions, 2004-2006

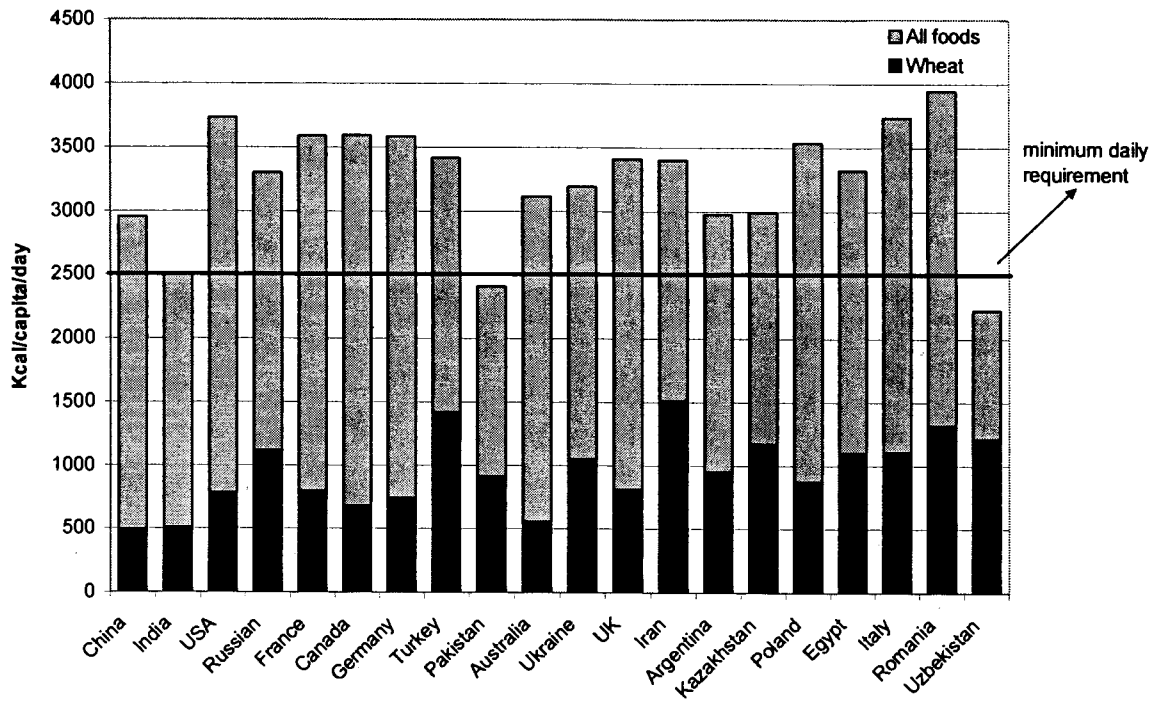
Regional contrasts	Area (million ha)	Yield (t ha ⁻¹)	Production (million t)
European Union	26	5.3	137
East Asia	23	4.3	98
South Asia + Afghanistan	38	2.5	97
North America	31	2.8	88
South America	9	2.4	22
Middle East + North Africa + Turkey	27	2.3	61
Eastern Europe + Russian Fed	31	2.2	69
Central Asia and Caucasus	15	1.4	22
Australia + New Zealand	13	1.5	19
Other	4	2.3	9
World	217	2.9	621
Developing countries	116	2.7	308
Developed countries	101	3.1	313
Country contrasts			
.. dominated by rainfed production			
Kazakhstan	12	0.9	12
Canada	10	2.6	27
United Kingdom	2	7.9	15
.. dominated by irrigated production			
India	26	2.6	70
Egypt	1	6.5	8

Source: CIMMYT databases.

Notes: South Asia includes Afghanistan (2.2 million ha). "Other" includes Sub-Saharan Africa (3 million ha).
Developed countries includes former USSR countries.

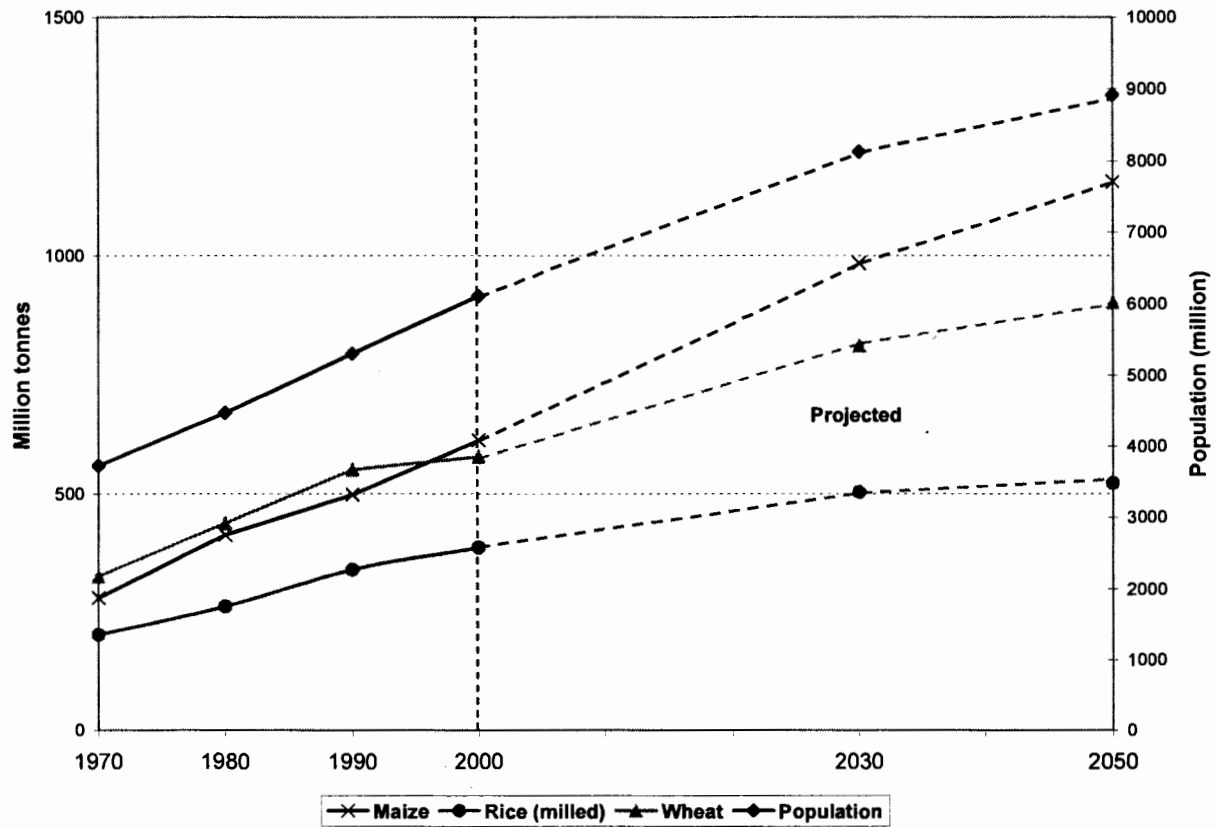
Table 2. Selected factors associated with yield performance over two periods of top 20 producing countries

<i>Col=1995-05 - → Row=1966-94</i>	< 0 % pa	0 – 2 % pa	2-4 % pa	> 4 % pa
< 0 % pa	No “top 20” countries	No “top 20” countries	No “top 20” countries	No “top 20” countries
0 – 2 % pa	Collapse of agricultural inputs and services, poor crop management, not yet recovered (e.g., Ukraine, Australia)	Lack of strong incentives for wheat of other crops with significant crop and livestock diversification throughout the period (e.g., Italy, Romania, Poland, Canada, USA)	Weak services and producer incentives, followed by reorganized inputs and markets, improved varieties and management (e.g., Russia)	Weak services and producer incentives, followed by improved markets, crop management (e.g., CA) and producer incentives, and specialization in wheat, i.e., lack of diversification options (e.g., Kazakhstan)
2-4 % pa	No “top 20” countries	Good varieties, management and subsidies, followed by crop and livestock diversification (e.g., Germany, France, UK, Spain, Turkey, Argentina, Egypt, India)	Continued stable and strong investment in irrigation, varieties, seed systems, crop management, subsidies (e.g., Pakistan, Iran)	No “top 20” countries
> 4 % pa	No “top 20” countries	Investment in varieties, crop management, irrigation and subsidies, followed by weakening demand and crop diversification (e.g., China)	No “top 20” countries	No “top 20” countries



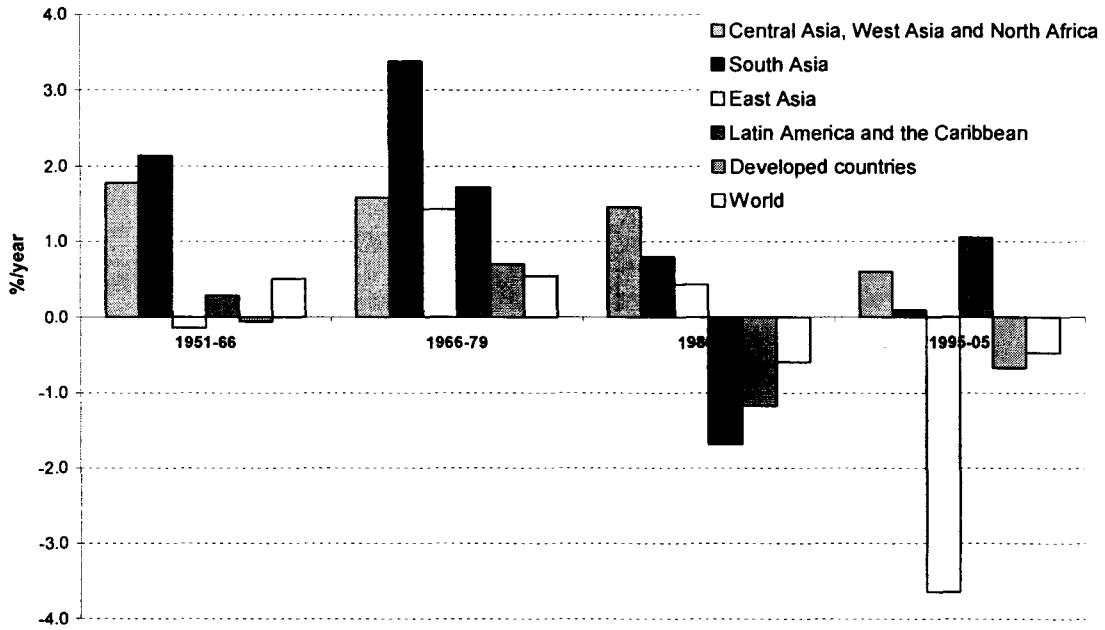
Source: FAOSTAT (2007); and Aromolaran (2004).

Figure 1. Share of wheat in food consumption in selected countries.



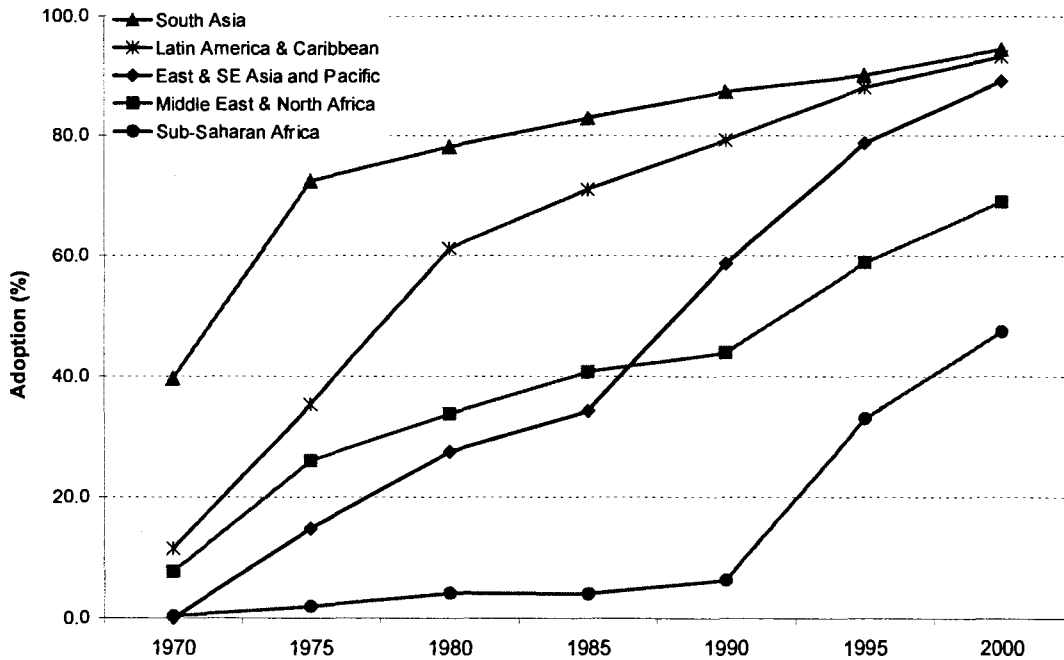
Source: FAO (2006).

Figure 2. World demand for wheat, maize, and rice, 1970-2050.



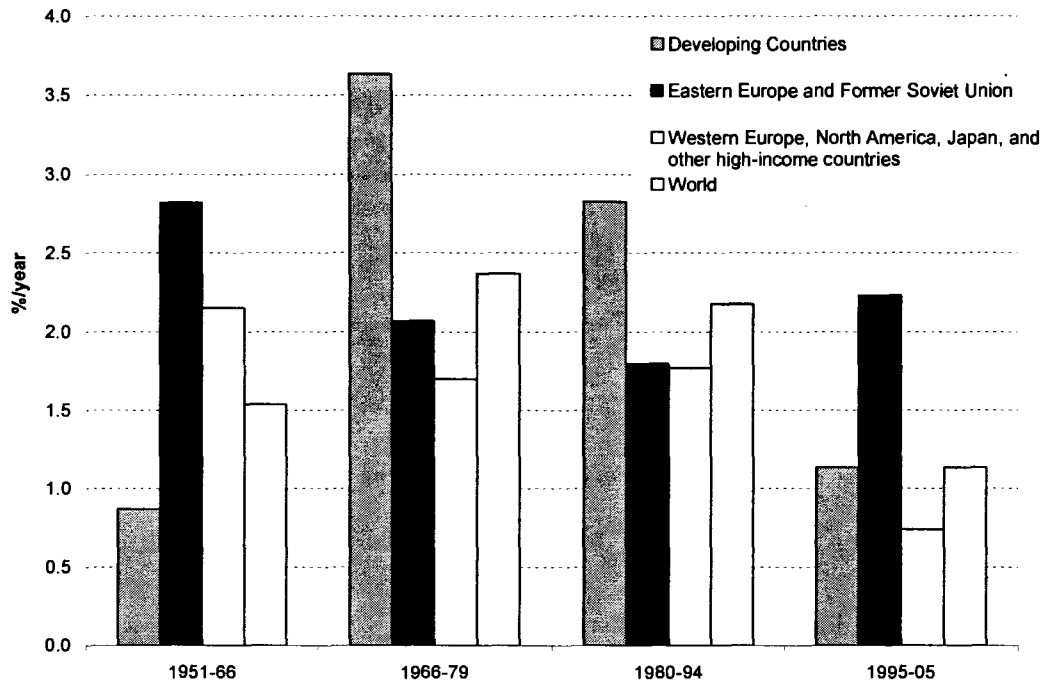
Source: FAOSTAT (2007).

Figure 3. Change in wheat area in selected regions, 1951-2005.



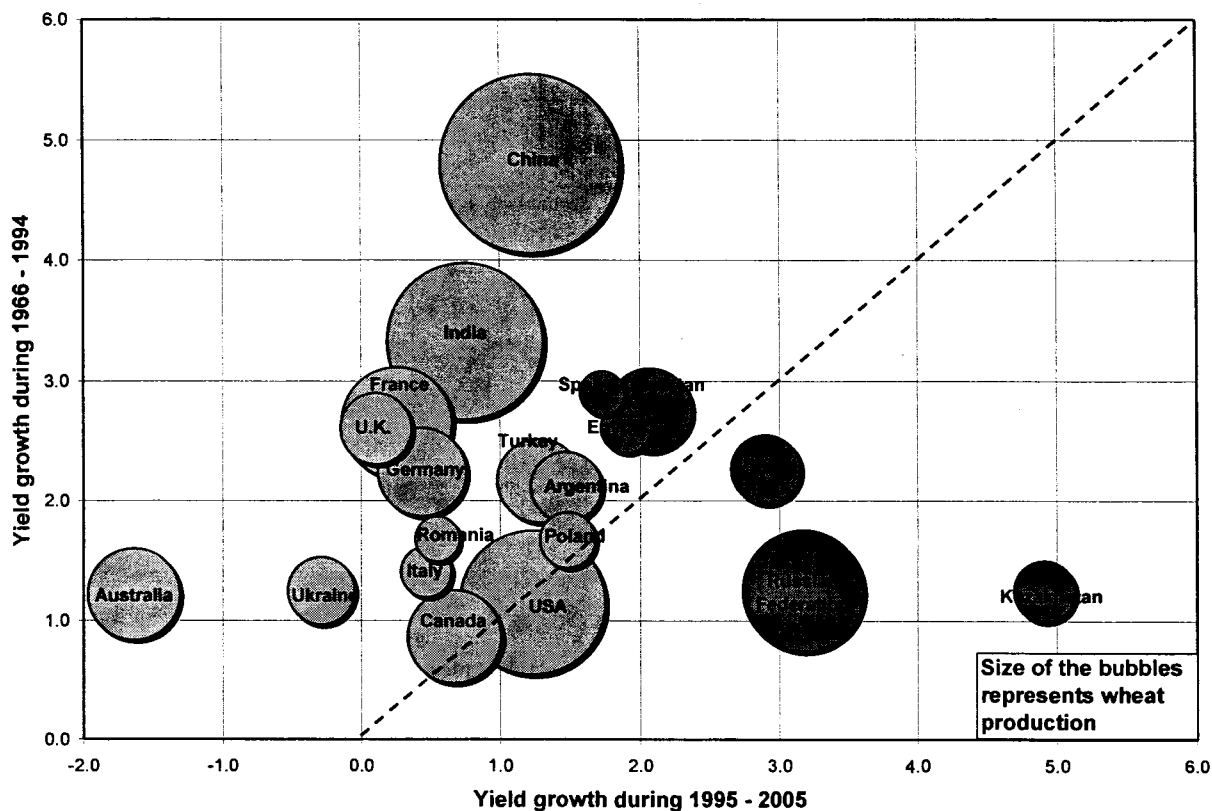
Source: Evenson and Gollin (unpublished).

Figure 4. Adoption of modern wheat varieties by region, 1961-2000.



Source: FAOSTAT (2007).

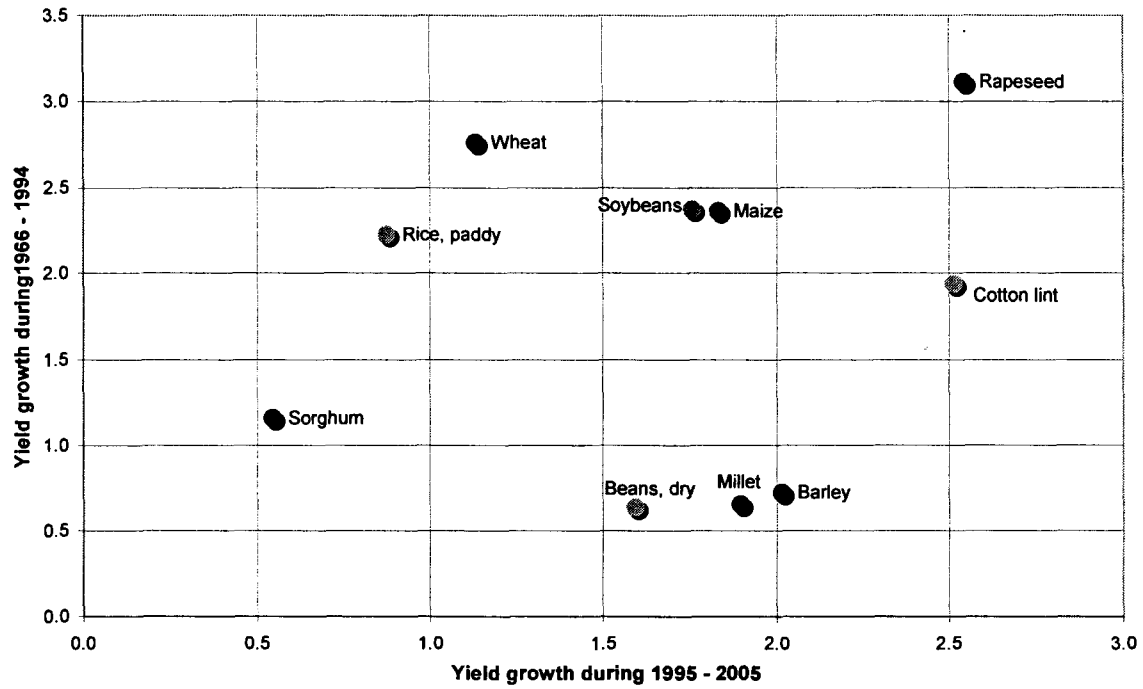
Figure 5. Growth rate of wheat yield by period and region, 1951-2005.



Source: FAOSTAT (2007).

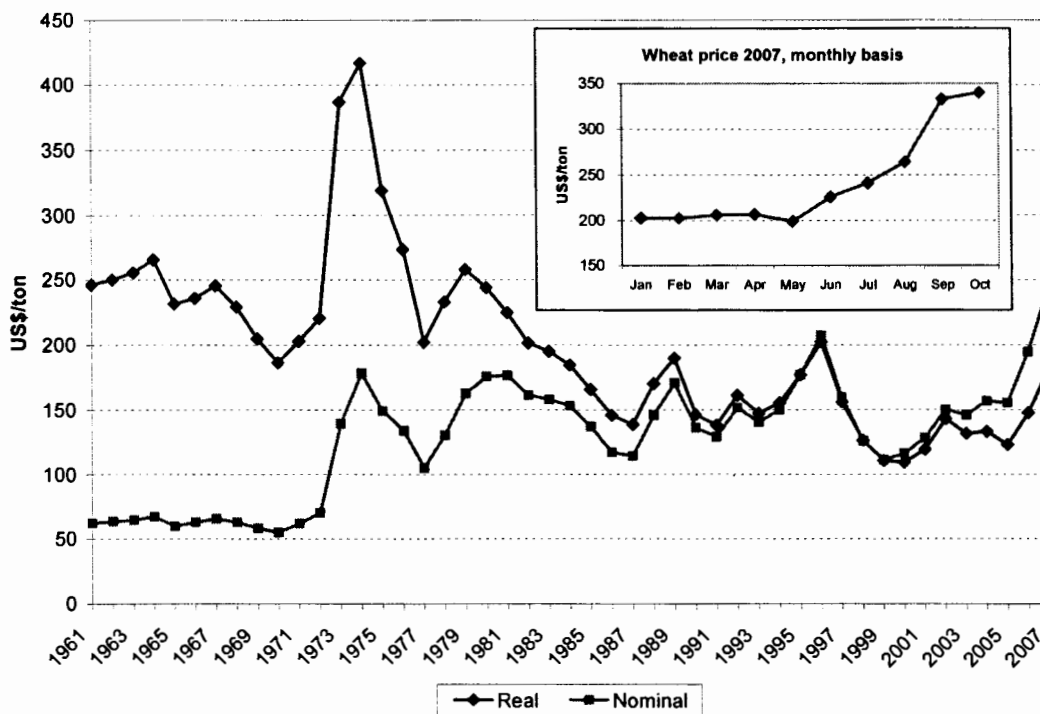
Note: Kazakhstan’s yield growth during period 1966-1994 was taken from average of Soviet Union.

Figure 6. Yield growth rate differentials by period (1966-1994 cf. 1995-2005) for the top 20 wheat producers.



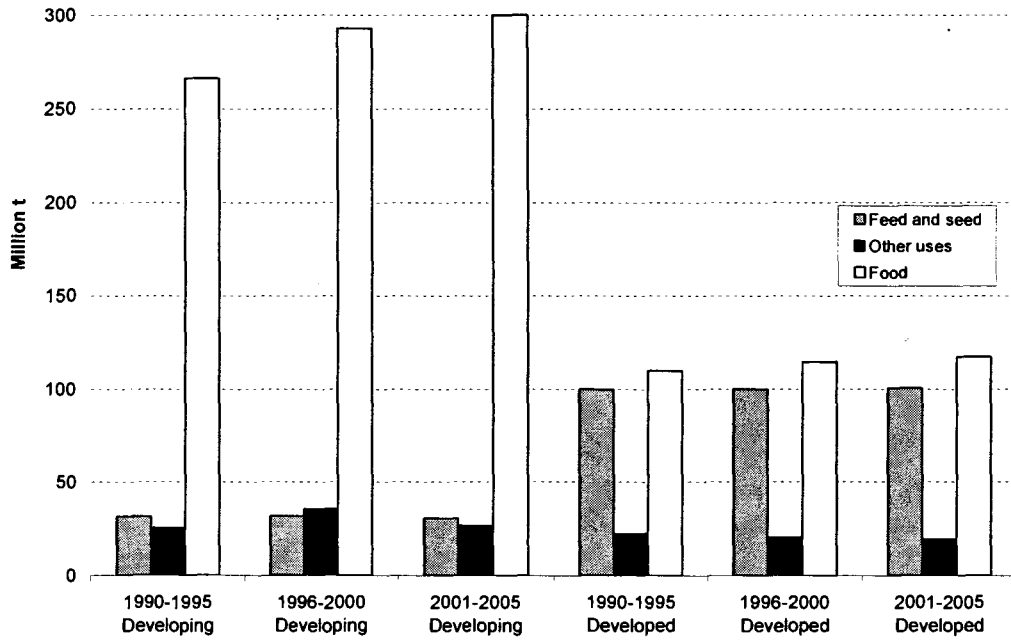
Source: FAOSTAT (2007).

Figure 7. Yield growth differentials by period (1966-1994 cf. 1995-2005) for major food and cotton crops in developing countries.



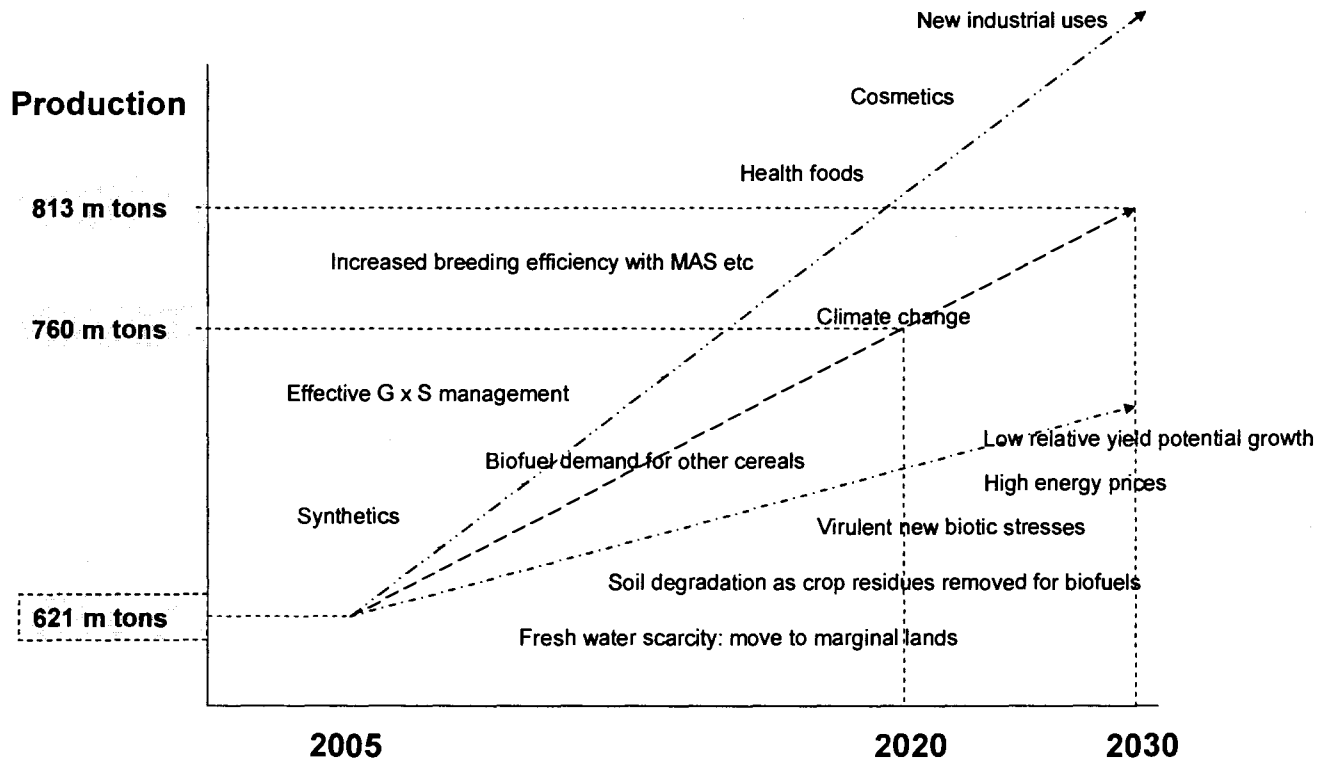
Source: USDA, Wheat Outlook, various issues.

Figure 8. International prices of wheat (real and nominal).



Source: FAOSTAT (2007).

Figure 9. Major uses of wheat for food and feed, 1990-2005.



Sources: Rosegrant (2001), FAO (2006), CIMMYT working papers (unpublished).

Figure 10. Wheat futures.



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