# Wheat Facts and Futures 2009

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CIMMYT
International Maize and Wheat Improvement Center

CIMMYT® (www.cimmyt.org) is an internationally funded, not-for-profit organization that conducts research and training related to maize and wheat throughout the developing world. Drawing on strong science and effective partnerships, CIMMYT works to create, share, and use knowledge and technology to increase food security, improve the productivity and profitability of farming systems, and sustain natural resources. CIMMYT is one of 15 Future Harvest Centers of the Consultative Group on International Agricultural Research (CGIAR) (www.cgiar.org). Financial support for CIMMYT's work comes from the members of the CGIAR, national governments, foundations, development banks, and other public and private agencies.

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**Abstract**: For nearly half a century, the international wheat breeding system has delivered improved high yielding varieties of wheat that created (along with rice) the Green Revolution and underpinned strong growth in wheat productivity in irrigated and rainfed, developed and underdeveloped, regions. Future priorities for breeding and complementary sciences will still include yield but will also diversify in response to changing market demands and growing environments, particulary in developing countries. It is argued that in the coming decades research on wheat quality characteristics will become increasingly important to plant breeders, whose work will be supported by the development of markers and advanced tools from molecular biology. Breeders will have to contend with increased heat stress and variability stemming from climate change, which is expected to create regional winners, as the northern high latitudes grow warmer and moister, and losers, as the sub-tropics and tropics increasingly suffer from heat stress and drought. Yield response of improved varieties in farmers' fields depends to a very great degree on sustainable systems management, which also is essential to reverse the ongoing degradation of agricultural resources. Finally, the importance of expanding the systems lens from farmers to policy makers, and of linking farmers, commerce, science, and policy is illustrated for the rice-wheat farming systems of South Asia.

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# Preface

The cultivation of wheat (*Triticum* spp.) reaches far back into history. 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, West Asia, and North Africa. Today, wheat is grown on more land area—over 240 million ha—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. Wheat is being harvested somewhere in the world in any given month.

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). If population growth continues at double the growth of wheat production, there will likely be serious difficulties in maintaining a wheat food supply for future generations. Recent fluctuations in wheat prices—in early 2008 the cost of a ton of wheat reached a record of nearly US$ 500—and the decline in global reserves of the grain underline the fragility of wheat supplies, particularly for the resource-poor. Predictions regarding the effects of global climate change on wheat suggest potential benefits for some areas and problems for others, but the major difficulties appear likely to be concentrated in developing country wheat lands. Less easy to predict but highly probable is the emergence and spread of new pests and pathogens in key wheat-growing regions. One example is the highly-virulent strain of wheat stem rust—known as Ug99—that appeared in eastern Africa a decade ago, has been sighted since in the Middle East, and could easily advance to South Asia soon on prevailing winds.

Offsetting the challenges described above are new opportunities to develop, disseminate, and market more productive, stress tolerant, and nutritive wheat varieties, and to perfect and promote production practices based on the principles of conservation agriculture that boost yields while conserving or enhancing critical resources like soil and water. New tools like molecular markers and genetic engineering promise major benefits for wheat productivity in the medium term.

Because agriculture is the foundation of rural development and economic growth, and given that wheat is such a prominent cereal in many regions, it is of critical importance to identify ways to restore wheat productivity growth in major producing areas around the globe. Greater wheat production could be achieved in several ways: by expanding wheat area, by making it more economically competitive with other crops, or by improving yield per unit area sown.

This document lays out in relevant detail key issues and trends in wheat-based agriculture, with special emphasis on the developing world, as well as market and science prospects for addressing challenges to meet the world's wheat demand. It is the latest in a series of periodic assessments of wheat research and development, particularly in developing regions. From the first Wheat Facts and Trends, which emulated in a modest way the World Development Report of the World Bank, CIMMYT has periodically issued new numbers in the series.

This particular flagship edition highlights six themes of major significance to wheat research in developing countries. The potential role of wheat quality in breeding and markets is analyzed, and the conclusion drawn that quality characteristics will grow in importance as a breeding objective. In another chapter, the opportunities offered by modern molecular biological tools are illustrated. Conversely, breeders will have to contend with increased heat stress and variability stemming from climate change, which is expected to create regional winners, as the northern high latitudes become warmer and wetter, and losers, as the sub-tropics and tropics increasingly suffer from heat stress and drought. The possibility of raising yield potential notwithstanding, yield response of improved varieties in farmers' fields depends to a very great degree on sustainable systems management, which also is essential to reverse the ongoing degradation of agricultural resources and is addressed in a section on conservation agriculture. The importance of expanding the systems lens from farmers to policy makers, and of linking farmers, commerce, science, and policy is illustrated in a chapter on the rice-wheat farming systems of South Asia. Finally, the publication depicts the diversity of wheat production systems and issues by profiling nine countries of differing circumstances, but which together account for 40% of the world's wheat output.

We hope this document will prove useful and engaging for all readers, and particularly for wheat scientists and research leaders in national agricultural research systems in developing countries. We welcome additional data on the wheat industry and challenges, as well as comments and suggestions on the content and focus of future editions of Wheat Facts and Futures.

**Thomas A. Lumpkin**
Director General
CIMMYT

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The Editors

# Overview: Transitioning Wheat Research 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, page 3, 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.[1] 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 productivity[2] 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

**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.

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

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

Egypt. Thus, there is clearly considerable scope for increasing productivity in many countries.

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 1,400 kcal per capita per day in Iran and Turkey. Overall across in the developing world, 16% of total dietary calories comes 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 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 year[3] (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 increase steadily, 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

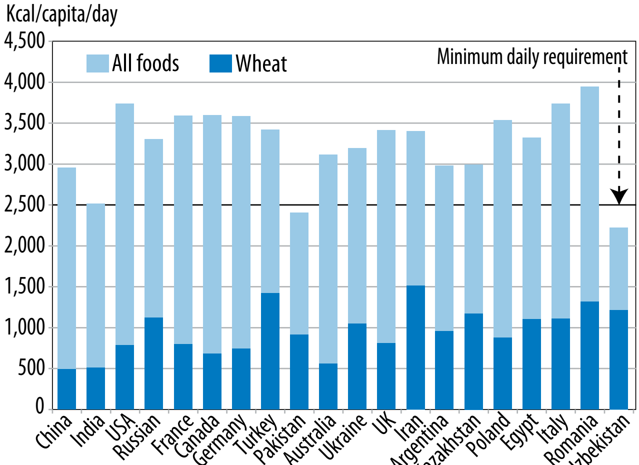

**Figure 1. Share of wheat in food consumption in selected countries.**
Source: FAOSTAT (2007) and Aromolaran (2004).

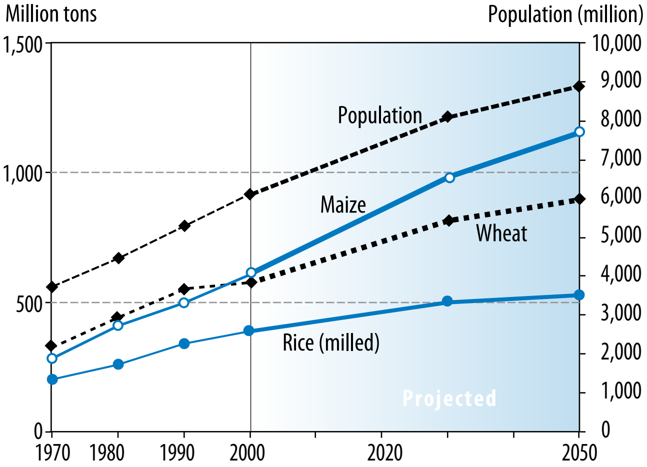

**Figure 2. World demand for wheat, maize, and rice, 1970-2050.**
Source: FAO (2006).

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

will grow faster than that for wheat, due both to the strong demand for maize as animal and poultry feed and 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 for 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).

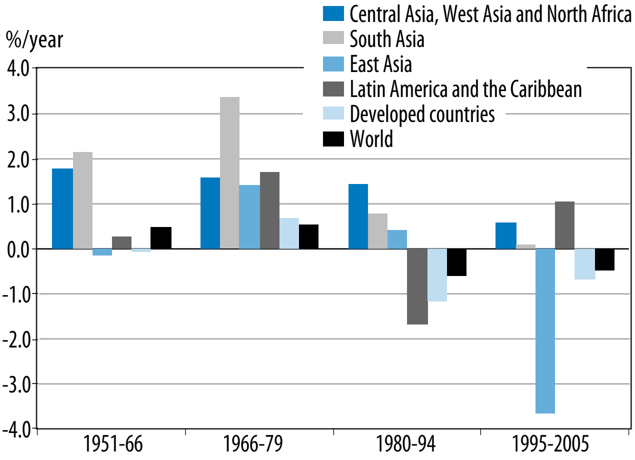

**Figure 3. Change in wheat area in selected regions, 1951-2005.**
Source: FAOSTAT (2007).

### Box 1. 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, 30% in the EU, and 10% in India. Most durum wheat production is based on spring varieties. Durum wheat is used mostly 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.

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 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).

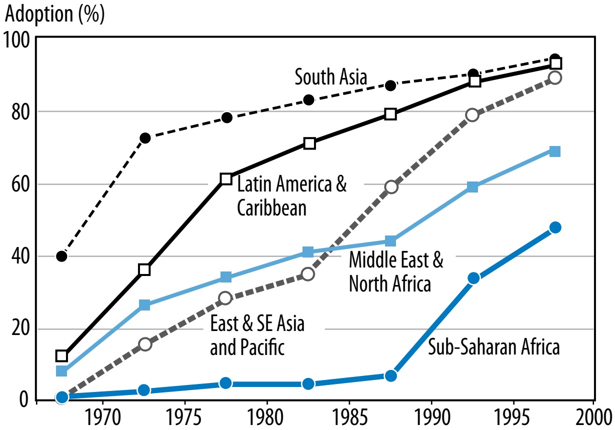

**Figure 4. Adoption of modern wheat varieties by region, 1961-2000.**
Source: Evenson and Gollin (unpublished).

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). This International Wheat Improvement Network (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.[4]

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

## 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 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).

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[4] Since the 1950s, wheat programs in major OECD countries contributed to, and also benefited from, the IWIN.

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.

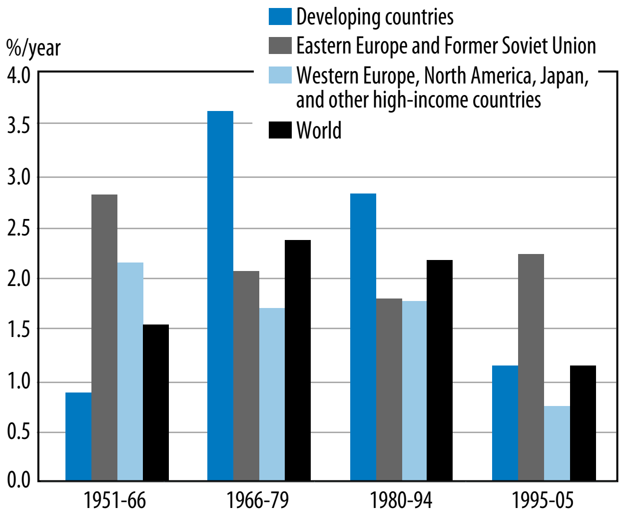

**Figure 5. Growth rate of wheat yield by period and region, 1951-2005.**
Source: FAOSTAT (2007).

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 1966-79. However, yield growth in developing countries slipped to 2.8% per annum during 1980-94, and then dropped to 1.1% per annum during 1995-2005 (Figure 5 and Aquino et al., this volume), once again falling below the population growth rate.[5] While poor productivity increases before the Green Revolution were compensated for by expansion in production area, Figure 3 indicates that area growth during 1995-2005 was around 1% per annum in Latin America

## 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 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 ever since.

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[5] While yield potential measured in breeders' fields continued to grow constantly during past decades, 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%.

[6] Cultivar = cultivated variety.

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 1995-2005. Some of the reasons for the reduced performance during that period are discussed below.

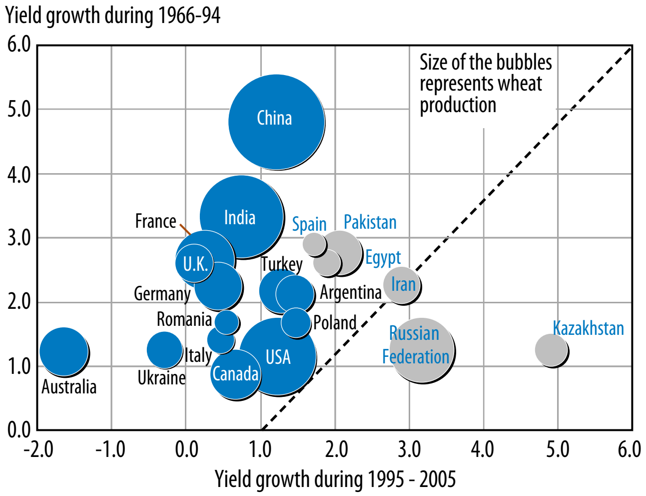

**Figure 6. Yield growth rate differentials by period (1966-94 cf. 1995-2005) for the top 20 wheat producers.**
Source: FAOSTAT (2007).
Note: Kazakhstan's yield growth during 1966-1994 was taken from average of Soviet Union.

To understand the causes for reduced performance after the mid-1990s, production data were disaggregated to the national level for the top 20 wheat producers. Figure 6 shows, for each of these countries, the average national yield growth during 1966-94 compared with that for 1995-2005.[7] 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 crop wheat in less productive areas. Overall, yield growth during 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.

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

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[7] 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.

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 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

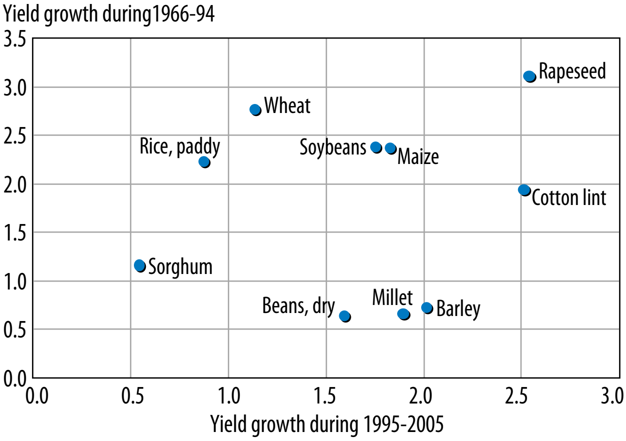

**Figure 7. Yield growth differentials by period (1966-94 cf. 1995-2005) for major food and cotton crops in developing countries.**
Source: FAOSTAT (2007).

**Table 2. Selected factors associated with yield performance over two periods for the top 20 wheat producers**

| ***Col=1995-05 - ⇨ Row=1966-94*** | **< 0 % pa** | **0 – 2 % pa** | **2-4 % pa** | **> 4 % pa** |
|---|---|---|---|---|
| < 0 % pa | No countries | No countries | No countries | No 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 cf other crops with significant crop and livestock diversification throughout the period (e.g., UK, 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 | Improved varieties and crop management (e.g. CA), followed by adverse climatic conditions, e.g.,prolonged drought, and emphasis on quality (no top 20 producers) | 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 countries |
| > 4 % pa | No countries | Investment in varieties, crop management, irrigation and subsidies, followed by weakening demand and crop diversification (e.g., China) | No countries | No countries |

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.

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, 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 to 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

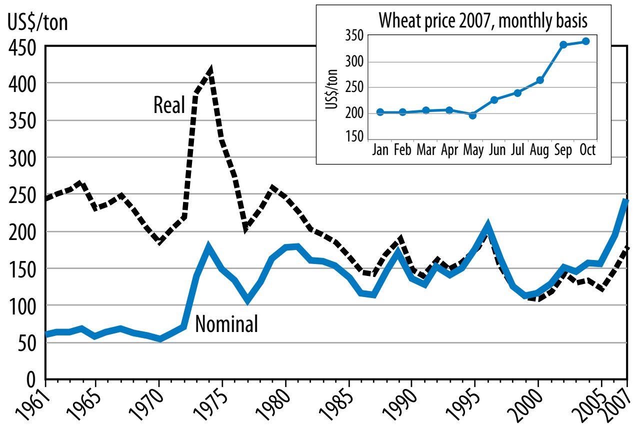

**Figure 8. International prices of wheat (real and nominal).**
Source: USDA, Wheat Outlook, various issues.

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 NARSs managers and senior wheat researchers must now confront 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 alternative scenarios for the 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"[8] 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.

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[8] Synthetic wheat is artificially developed; in CIMMYT's case, this relates to hybrids containing the wheat genomes donated by wheat's progenitors.

**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 increasing 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.[9]

**Knowledge and capacity**. The improvement of databases for priority setting offers the means to increase payoffs through optimizing investments in wheat 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), and mega-environments should be refined to reflect these 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. The FAO-World Bank farming systems classification of Dixon et al. (2001) provides an example. Using such a framework at global or national levels, together with spatial 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 smallholder farming.

**Agricultural resources**. Environmental concerns, stagnating yields in many wheat-based systems, declining soil fertility, and global climate change 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

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[9] Domestic wheat prices are also substantially above world prices in the EU and, especially, Switzerland.

needs on average 900 L of water as compared to 1,400 L for maize and 1,900 L for rice. Wheat is, therefore, the most water use efficient of the three major global cereal commodities. However, the variation for water use efficiency (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 5,000 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 scarcity of water, 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 scenarios for future 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 t ha$^{-1}$ (up from the present 2.9 t 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.

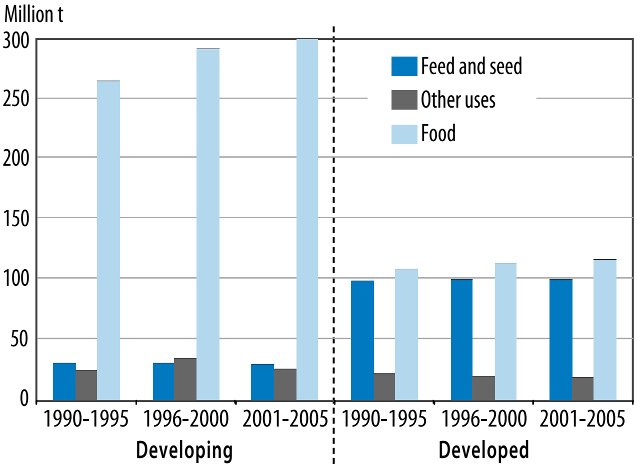

**Figure 9. Major uses of wheat for food and feed, 1990-2005.**
Source: FAOSTAT (2007).

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 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 indicates that wheat production (and consumption) will grow at approximately 1.6% per year, so 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 marker assisted selection (MAS); hybrid or GM wheat; increasing private sector investment; the growing demand for health foods; and 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, specifically 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

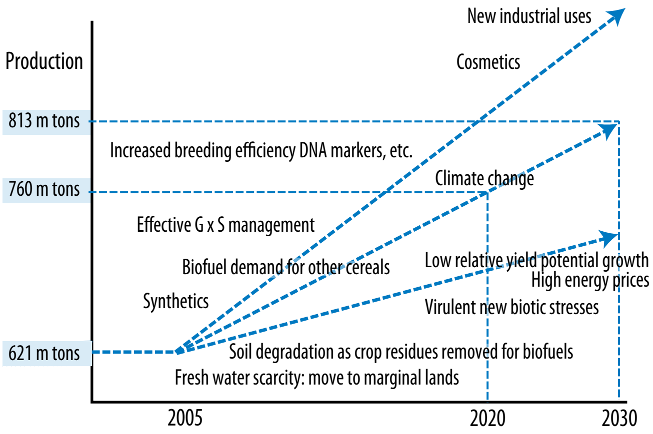

**Figure 10. Wheat futures.**
Sources: Rosegrant (2001), FAO (2006), CIMMYT working papers (unpublished).

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 biofuel 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 $CO_2$ in the atmosphere, it is sensitive to high temperatures, 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 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 in farmers' field, which has aggravated 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 Ug99, 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.

**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.[10] Over one-third of 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 (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. Moreover, 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, most 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 spreads 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, such situations are likely to become more common.

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[10] 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.

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 $CO_2$ emissions. This illustrates that long-term, economically important changes in pathogen populations can be influenced by anthropogenically-induced environmental changes, of which $CO_2$ 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, also known as 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

### Box 4. From Complacency to Crisis: Stem Rust Race Ug99

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 Ug99 represents a major threat to global wheat production.

A concerted, global research effort to combat Ug99 and other wheat rusts—the Borlaug Global Rust Initiative (www.globalrust.org)—is being led by, among others, CIMMYT, the International Center for Agricultural Research in the Dry Areas (ICARDA), Cornell University, FAO, and the Indian Council of Agricultural Research (ICAR). 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.

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* spp. (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 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 LDCs, are derived mostly from public donors and often spread over many research programs, making each investment relatively small and often less efficient. Average aggregate yields 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 for 1976-81 to below 4% for 1991-96. In 2000, in developed countries the public and private sectors 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). A strong public sector working cooperatively with the private sector is essential to ensure benefits from the gene revolution (Pingali and Raney 2005), but 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 obtain 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 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 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 increased farm-level crop diversity in various regions. 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 is thus 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. 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 contributing 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 10 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 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: 1) of limited heterotic advantage: historically only about a 10% advantage is commonly found, though introducing new genetic diversity (e.g., through synthetics) may increase heterosis; 2) of a lack of advantage in terms of agronomic, quality, or disease resistance traits; 3) seed production costs are higher than gains due to the heterotic yield advantage; and, probably most importantly, 4) 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 seed.

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] 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 hand, increasing knowledge of the wheat genome and subsequent gene discovery will make MAS more important, since 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 emerging options from biotechnology on the other, we refrain from making a prediction about the future of hybrid wheat.

**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 in 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 HarvestPlus Challenge Program of the CGIAR is attempting to introgress genes for high micronutrient grain content—in particular iron and zinc—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, NARSs 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 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 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 LDCs) 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 wheat improvement at CIMMYT.

**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. 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.

### 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, so CIMMYT emphasizes the development of cultivars that combine high yield potential with tolerance to severe drought. 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.

**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 stop producing wheat or 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],[11] the IWIN website,[12] and the Cereal Knowledge Bank[13]) 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 from field trials in various environments representative of 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 access up-to-date global and local market information to guide decision-making. One example is e-Chopal, the electronic market information system in northern India. On-line tools for monitoring the epidemiological status of pests and diseases will also be beneficial.[14] To address global challenges in wheat science and production, the exchange of both wheat genetic material and associated knowledge through existing networks and new partnerships (e.g., IWIN) will be a critically important international public good that must remain freely available to achieve 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

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[11] www.cimmyt.org/english/docs/proceedings/gis01/linkingICIS/linking_stapper.htm.

[12] www.cimmyt.org/english/wps/obtain_seed/iwin/index.htm.

[13] knowledgebank.cimmyt.org.

[14] www.globalrust.org/.

"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 agriceutical 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 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-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 slower growth in 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 with 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 1995-2006, as with most other major crops. Constraining factors include declining soil fertility and water tables, increased intensity of biotic stresses, higher energy and input prices, a stronger cost-price squeeze on farmers, and weaker incentives for varietal replacement, against a backdrop of low grain prices and diminishing research investments. Conversely, a number of positive factors 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. Major factors that could accelerate or constrain productivity increases and demand include biofuels, climate change, 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; cost-saving production 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 reduce poverty, the primary challenges 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 farm 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. It is also 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 the 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 LDCs as traditional products, 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 for consistent quality. Moreover, the growing purchasing power of middle-class urban consumers will create new markets for higher-value wheat products with local quality characteristics. There are major new end-uses for wheat that will add to its industrial value and increase the demand for high-quality wheat. This in turn will require 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 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 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 to generate widely applicable systems management solutions will be best served by strengthening an advanced, global strategic science platform, such as that managed by CIMMYT in Mexico, linked to cropping systems research hubs in major 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 water and nutrient use efficiency, 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 show how this could be done (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 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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# Wheat Quality in the Developing World: Trends and Opportunities

**E. Meng, A. Loyns, and R.J. Peña**

## Introduction

Significant changes in wheat consumption patterns and end uses in developing countries are increasingly focusing attention on wheat quality as a breeding target in national programs and as a potential source of income for local producers. While breeding for yield and resistance/tolerance to biotic and abiotic stresses remains a priority, improving wheat quality has become an equally important focus in many national programs. Although the degree of priority given to wheat quality is uneven across wheat-producing developing countries, these measures reflect a global movement towards the "de-commodification" of grain markets, where value can be potentially created through breeding wheat with specific quality characteristics.

Achieving improvements in the supply of wheat with desired quality characteristics at the producer level requires concerted efforts at several levels. Certainly, an explicit focus on quality improvement signals that wheat quality has higher priority. However, clear quality standards correlated with specific end uses, the means to identify varieties possessing those qualities, and systems to provide quality assurance are also necessary. Local capacity to segregate qualities upon delivery of the grain must exist to some extent as well. Without the ability to differentiate among varieties having different quality characteristics, farmers may not have the incentive to grow quality wheats, as quality traits are likely to be invisible.

Experience from major exporting countries with well established grain marketing systems shows that appropriate institutions and infrastructure must be in place for the transmission of information and incentives among participants in the wheat value chain, as well as for quality assurance (Golan et al. 2004; Smyth and Phillips 2002). Without a facilitating environment, it is less likely that domestic wheat grain with the desired end-use quality characteristics can be produced and delivered to meet growing demand in developing countries.

In this article, we discuss challenges and opportunities for improving wheat quality throughout the wheat value chain in developing countries, with emphasis on the plant breeding/variety development, production, and marketing systems. We discuss trends in wheat consumption in developing countries and their implications for wheat quality. In the second section, we address general issues in defining and standardizing the supply of wheat quality before focusing, in the third section, on the requirements, constraints, and opportunities for the development of wheat value chains specifically in developing countries. We conclude with a discussion of the challenges involved in breeding for wheat quality within this milieu.

## Changing Wheat End Use Patterns

Much of the increased emphasis on improving wheat quality in developing countries is driven by changing patterns in food consumption throughout the developing world. Trends towards buying more convenient and processed wheat products, both traditional and new, are in turn are influenced by urbanization, rising household incomes, and the increasing opportunity costs of labor. Broad patterns of changes in Asian diets have been described in China, India, and Indonesia (Gale and Huang 2007, Fabiosa 2006, Du et al. 2004, Pingali 2006, Du et al. 2002). A combination of demand and supply factors play a role in this region: particularly important are rising incomes, urbanization, and lifestyle changes, as well as increasing global integration, the growing presence of formal markets and supermarkets, and lower transportation costs (Pingali 2006). Differences in consumer demand for wheat products can occur across: a) different income groups; b) rural and urban populations; and c) different geographical regions of a country. Changes can also take place for a given population group over time.

Consumption changes have largely been associated with general dietary shifts from grains and vegetables to meats and other sources of fat. For cereals specifically, as incomes rise, consumption trends indicate a continuation of general shifts from coarse cereals, such as maize and millet, to refined cereals, such as wheat and rice. A shift in consumption patterns from rice to wheat and changes within the consumption of a given cereal have also been observed in several regions of Asia.

Changes in the consumption of wheat take the form both of shifts from household preparation of traditional products to the purchase of processed, ready-to-eat traditional foods outside the home and of increased consumption of western-type pan and leavened breads, cakes, pastries, and cookies. Five- to ten-year projections for flour utilization by the wheat industry in China predict a decrease in the share of flour utilized for noodles and steamed bread (from 80% to 76%); a decrease in the share of cookies, cakes, and fried products (from 12% to 8%); and an increase in the share of western bread products (from 8% to 16%) (Wang et al. 2004). While these estimates show the increasing importance of new products, they also emphasize the continued importance of traditionally-consumed wheat products that are being accessed more and more by households in non-traditional ways.

The growing preference for convenience and ready-made foods has been associated with urbanization and lifestyle changes taking place in developing countries globally. Data from China show that while reliance on household-produced grain is still high, with an average share of 83% of total consumption across rural households in China, there is a shift in expenditures from household-produced food to purchased food and food consumed-away-from-home (Gale et al. 2005). The share of grain purchases away-from-home is low relative to food groups such as meat and poultry, but likely also includes shifts in demand across different grain end-uses associated with convenience and "higher" quality (Gale et al. 2005). Although attention has focused on China and India due to their large populations, urbanization, and rapid economic growth, similar patterns of change can be observed throughout Asia, North Africa, and Latin America.

The changing consumption patterns in wheat are often masked by data aggregation because available data separating wheat consumption by specific end product and by income groups are very limited. Research on the effect that changes in income have on the demand for grain[1] using national income and expenditure data from rural households in China suggests income elasticities[2] of grain at 0.18, 0.06,

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[1] The category of grain in China includes cereals, of which wheat and rice are by far the most important, as well as potatoes and beans.

[2] An income elasticity of demand measures the effect of an increase in income on a change in the quantity of a good demanded. The higher the income elasticity, the greater the demand for that good when income increases. Conversely, the lower the income elasticity, the smaller the effect of an increase in income on demand for the good. Normal goods have a positive income elasticity of demand between 0 and 1; demand thus rises with income, but less than proportionately. Luxury goods, for which demand rises more than proportionately to an increase in income, are characterized by an income elasticity of demand greater than 1. Finally, inferior goods are characterized by a negative income elasticity of demand such that demand for the good falls as income rises.

and 0.02 for the lowest, middle, and highest income quintiles, respectively, of rural households in 2003. Although they are all positive, the income elasticities indicate that an increase in income results in little to no change in the demand for grain within any of the income categories. Income elasticities for grain in urban households grouped into four income levels decreased from a level just above zero for the lowest income category to small but negative levels for the other three income categories (Table 1). However, a comparison of grain quantity and quality elasticities in urban households indicates the willingness of households with rising income levels to pay for grain quality, likely in the form of processed traditional foods and other, new, "high value" grain products.

**Table 1. Quality and quantity elasticities for grain by income level, urban households, 2002-2003**

| Income category (yuan) | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2,500 | | 7,500 | | 10,000 | | 22,000 | |
| Quality | Quantity | Quality | Quantity | Quality | Quantity | Quality | Quantity |
| 0.11 | 0.00 | 0.23 | -0.09 | 0.25 | -0.10 | 0.27 | -0.11 |

Source: Gale and Huang, 2007.

In another example from Asia regarding the shift from consuming household-prepared foods to processed foods, in Indonesia (not a wheat producing country), per capita consumption of wheat-based products has been increasing rapidly in recent years, but is still relatively low. Monthly per capita consumption of wheat products in 1999 was 0.33 kg, with instant noodles, household wheat flour purchases, and bread being the most popular. The income elasticity for all wheat products estimated using 1999 data was high at 0.44 and attributed both to a higher probability of consumption in previously non-consuming households and an increased level of consumption in already-consuming households. Income elasticity specifically for noodles, the fastest growing wheat product due largely to their convenience, was also high, particularly in urban areas (Fabiosa 2006).

It will be important to understand and address the implications for wheat quality of the shift from home preparation to increased industrial processing in the developing world. Changing consumption patterns drive changes in the processing and supply of wheat products. The growing presence of large baking plants and supermarket bakeries reflects increased mechanization and a growing awareness of end-use quality characteristics. Led by the growing demand for convenience products in the form of ready-made, frozen, microwaveable, and instant products, food production is becoming more mechanized, and a larger range of food products, both traditional and new, is being produced in larger commercial plants and sold in supermarkets. To satisfy consumer needs, the wheat processing industry demands wheat with improved and well defined characteristics. A 2-3% higher flour extraction rate in the mill and better protein and starch functionality that improve processing performance and food attributes, including extended shelf-life, mean better profits for the miller and the baker, and satisfaction for the consumer. The ability to supply wheat that meets local demand for specific end-use quality requirements will thus become more and more crucial. Industrial food processing requires wheat quality attributes that often cannot be met by wheat for traditional foods. Greater resistance to mechanical dough mixing under pre-established, relatively short mixing times and medium-to-high mixing speeds are needed, as well as a minimum of grain hardness to facilitate high dough-water absorption that renders food products with appropriate texture and prolonged shelf life. Equally important, mechanized processes require minimal variability between delivered lots and over time, and the standardized means to ensure that desired quality criteria have been met. Table 2 summarizes the principal traditional and non-traditional wheat products consumed in selected regions, as well as the target traits to meet requirements for expanded industrial processing of wheat products.

## What is Wheat Quality?

In general, for wheat to attain maximum value in a commercial wheat system, it must: (1) possess inherent characteristics for the intended end-use; (2) be relatively free of foreign material and contamination; and (3) be presented in a manner that will attract buyer interest based on reasonable assurance that the wheat is what it appears, or is claimed, to be. These elements summarize the basic "wheat quality" requirements in a commercial setting. As the quality of wheat is ultimately determined by its suitability for the use for which it is intended, the term "high quality wheat" carries little meaning in and of itself outside of a defined use-context.

In addition to specific end-use characteristics, however, industrial processing requires quality consistency and quality assurance measures (Wilson 2006a). Other aspects of wheat quality associated with food safety and nutritional attributes are also receiving increasing attention in the scientific and policy arenas.

### "High" quality versus "end-use" or "desired" quality

Certain classes of wheat are more suitable than others for the production of different wheat products. Changing consumption patterns and processing demands in developing countries result in the utilization of wheat in

**Table 2. Traditional and non-traditional wheat products and future end-use requirements in developing countries**

| Country/ Region | Traditional wheat products | Non-traditional wheat products | Traits targeted in locally-produced wheat to meet industrial processing requirements for traditional and non-traditional products |
|---|---|---|---|
| **India** | Bread wheat: Flat breads (chapati, paratha, nan), biscuits.<br>Durum wheat: porridge, traditional sweet goods. | Bread wheat: leavened bread, pan bread, buns, convenience foods (pre-cooked, ready-made), and frozen products.<br>Durum wheat: pasta. | Bread wheat: enhance grain protein and gluten strength and extensibility.<br>Durum wheat: enhance grain protein, gluten strength, and endosperm yellowness. |
| **North Africa; Near and Middle East** | Bread wheat: traditional unleavened flat breads and leavened bread, European style leavened bread.<br>Durum wheat: couscous, bulgur, regional breads. | Bread wheat: pan bread and buns, convenience foods (pre-cooked, ready-made), frozen products.<br>Durum wheat: pasta. | Bread wheat: enhance grain hardness, gluten strength, and extensibility.<br>Durum wheat: enhance gluten strength and endosperm yellowness. |
| **China and South-East Asia** | Bread wheat: noodles, dumplings, steamed bread, biscuits, Chinese pancakes, and other fried products. | Bread wheat: leavened bread, pan bread and buns, convenience foods (pre-cooked, ready-made), and frozen products. | Bread wheat: enhance grain hardness, flour whiteness, gluten strength, and extensibility. |
| **Latin America** | Bread wheat: white and sweet artisan breads, flat bread (flour tortilla), European style leavened bread, pan bread.<br>Durum wheat: pasta. | Bread wheat: convenience foods (pre-cooked, ready-made), instant noodles, and frozen products. | Bread wheat: enhance gluten strength and extensibility.<br>Durum wheat: enhance gluten strength and endosperm yellowness. |
| **Central Asia** | Bread wheat: flat breads (tandyr), dark and white pan-type bread, cookies. | Bread wheat: leavened bread and buns convenience, foods (pre-cooked, ready-made), frozen products.<br>Durum wheat: pasta. | Bread wheat: enhance gluten strength and extensibility.<br>Durum wheat: enhance gluten strength and endosperm yellowness. |
| **Sub-Saharan Africa** | Bread wheat: European style leavened bread, pan bread, flatbread, steamed bread.<br>Durum wheat (Ethiopia): porridge, flat bread. | Bread wheat: pan bread and buns, convenience foods (pre-cooked, ready-made), frozen products, and cookies.<br>Durum wheat: pasta. | Bread wheat: enhance grain protein, gluten strength and extensibility.<br>Durum wheat: enhance gluten strength and endosperm yellowness. |

ways that often require a different, but not necessarily "better," set of quality traits from those suitable for the household or small-scale preparation of traditional or new wheat products. In practice, objective and easily measurable criteria that better reflect end-use needs and values than ungrouped batches are needed to segregate wheat for specific end-uses. Within these segregated categories (reflecting end-use value), one can speak of higher or lower "quality" and increased or decreased relative value.[3]

Desired end-use quality may also vary by geographic region and, of particular significance to developing countries, with the type and scale of processing. Characteristics preferred by subsistence and semi-subsistence farmers for wheat end-uses such as noodles, steamed breads, chapati, and other traditional flatbreads commonly prepared by hand in small quantities for home consumption may differ from those demanded by semi-mechanized, small milling/baking enterprises and, in turn, from those needed by fully mechanized, large-scale commercial enterprises. Moreover, the adjustments in ingredients or preparation methods and time that can be made manually in response to variation in wheat characteristics are not possible in mechanized processes, which are much less flexible.

In India, for example, a large share of wheat production is milled as whole-grain (atta) flour using stone-mills in villages and small towns. Dough variability caused by unstable wheat quality can be managed within the household by manually adjusting the ingredients and/or kneading time. However, the production process in a mechanized baking enterprise is much less forgiving. Commercial manufacturers of both traditional and nontraditional (western type) wheat-based foods require uniformity in dough development time, in overall dough handling properties, and in the textural properties of the end product, plus stability or tolerance to over-mixing.

Specific categories of quality attributes are increasingly identified within a defined context; i.e., quality related to a particular end-use (Table 3). Many diverse wheat products, classified broadly as leavened or unleavened (flat) breads and as flour noodles, are made with doughs whose water absorption capacity and visco-elastic properties depend mainly on well known core traits. Likewise, the processing and end-use quality of the main durum wheat-based products (e.g., pasta, couscous, and porridge) depends on similar grain quality characteristics. The core quality traits for bread wheat are grain hardness, protein content, gluten strength, and extensibility. For durum wheat, they are protein content, gluten strength, and endosperm yellow pigment content. In general, bread wheat possessing medium-hard grain, intermediate (11.5-12.5%) protein, and medium-to-strong gluten with at least intermediate extensibility and intermediate-to-high starch paste viscosity, as well as durum wheat characterized by vitreous kernels, intermediate-to-high protein, and medium-to-strong gluten, are acceptable for industrial processing for most global wheat products (Peña et al. 2002).

### Food safety and nutritional attributes

Food safety considerations have been emphasized due to concerns over potential harmful effects on human health and the growing role of sanitary and phyto-sanitary (SPS) issues in international trade. A key food safety issue associated with grain involves mycotoxin contamination affecting food and feed grains in the field and during grain storage. Mycotoxin contamination is difficult to detect and not necessarily removed by processing or cooking. All five broad groups of mycotoxins (aflatoxin, vomitoxin, ochratoxin A, fumonisin, and zearalenon) have been linked

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[3] An alternative view of wheat quality based on end-use characteristics is that there are intrinsic wheat characteristics that generally command higher value, therefore those wheats are of "higher quality."

to health concerns and are subject to SPS or other regulatory measures (Dohlman 2003). The fungi most relevant for wheat are *Fusarium graminearum* and *F. culmorum*, which produce deoxynivalenol (DON), nivalenol (NIV), and zearalenone (ZEA), identified by the International Agency for Research on Cancer as a possible carcinogen (Dohlman 2003).

The Codex Alimentarius Commission of the United Nations sets advisory standards for mycotoxins at an international level, but national standards can be more stringent. The number of nations that adopted mycotoxin regulations increased significantly from the mid-1980s to the mid-1990s, and developing countries have experienced losses in export markets as a result of mycotoxin contamination or the implementation of stricter regulations by importing countries (Dohlman 2003). Losses from vomitoxin contamination have affected wheat farmers in North America (Johnson et al. 2001).

Global attention has also become more focused on the potential to improve health status by increasing wheat's nutritional attributes. Under the auspices of HarvestPlus, an initiative within the Consultative Group for International Agricultural Research (CGIAR), wheat varieties with increased concentrations of iron and zinc in the grain are being developed with the objective of alleviating micronutrient malnutrition in poor rural populations in the developing world (Ortiz-Monasterio et al. 2007). Initial target areas for biofortified wheat are regions in India and Pakistan with high per capita wheat consumption, where households consume the wheat they produce. In response to global trends in obesity and associated health issues of hypertension, coronary disease, and diabetes, other wheat quality traits are being investigated. These include increased levels of bran; soluble and insoluble fiber to assist in controlling blood sugar levels and delaying hunger through increased satiation; and increased amounts of high amylose starch, a resistant and slowly-digestible starch. Growing consumer interest in organic wheat will likely also present new challenges for wheat improvement.

## Consistency of supply of quality attributes/ quality control systems

A functioning wheat value chain is a prerequisite for a quality control system to work properly. A value chain describes the full range of activities required to bring a product or service from conception to final consumption (Kaplinsky and Morris 2000) and includes: (1) actors and institutions (wheat scientists, farmers, input suppliers, traders, processors, retailers, and consumers); (2) the enabling (or disabling) institutional and policy environment in which the supply chain operates; and (3) services necessary for its operation, such as credit, market information, transportation, and storage. A functioning quality control system incorporates rules and standards to govern the system; mechanisms for the transmission of information and incentives to adhere to the rules and standards; institutions to administer those rules and

**Table 3. A rough guide to key end-use characteristics targeted in the development of cultivars for selected wheat products**

| Product | Grain color | Flour protein (%) | Grain hardness | Flour pigment | Dough strength | Dough extensibility |
|---|---|---|---|---|---|---|
| Leavened bread | Red/white | High | Hard/semi-hard | Low | Strong/medium | High |
| Flat bread | White | Intermediate | Hard/semi-hard | Low | Medium/strong | High |
| Steamed bread | White/red | Intermediate | Semi-hard | Low | Medium | High |
| White, salted noodle | White | Intermediate | Soft/semi-soft | Low | Medium | Intermediate |
| Yellow, alkaline noodle | White/red | Low/high | Hard/semi-hard | Not defined | Medium/strong | Intermediate |
| Biscuits (cookies) and cakes | Red/white | Low | Soft | Low | Weak | Intermediate |
| Alimentary pasta (Durum wheat) | Amber | Intermediate/high | Vitreous | High | Strong | Low |

Source: Peña et al. 2002.

standards; technologies to facilitate their implementation; and clear determination, not only of the costs and rewards, but also of to and by whom they are paid.

The scope and range of a quality control system can vary considerably. A system for quality control and assurance can be formally imposed and implemented at the national level, as is the case of the wheat industries in Australia, Canada, and the USA, or it can be more informal and locally implemented through direct wheat inspections, as is the case among farmers and buyers in the private wheat markets of central India (Ramesh 2006; Gandhi 2006). As processing, milling, and baking become more mechanized and industrialized, and as markets become more complex, buyers and users require increasing assurance that desired quality attributes are present in the wheat delivered. They demand that wheat delivered at different times and from different producers and locations be reasonably similar in terms of processing and end-use requirements; this, in turn, necessitates more transparent and easily transmittable rules and standards.

The formulation and development of a formal quality control system is not an easy task; even in major commercial wheat-producing countries where they have been in place for decades, systems for quality control continue to evolve, particularly as priorities change over time. The system should reflect national policy, economic philosophy, and the prominence of wheat in domestic production versus import/export markets. The large commercial wheat-producing and exporting countries have all implemented different quality control systems that reflect their own particular conditions (Table 4).

One common characteristic of these systems is the use of grades and standards to facilitate the segregation of grain into a few categories with uniform characteristics. Segregation enables buying and selling wheat by description rather than direct inspection; transmits information on grain characteristics of value for marketing and processing purposes; and provides tools for the market to generate incentives for quality improvement. An example is the development of improved wheat quality in Australia, where key roles have been attributed to the implementation of classification and grading standards (Brennan 1997). By reducing the incidence of variability and facilitating price/quality comparisons, grades and standards also reduce information asymmetries and search costs (Wilson 2006a). Quality standards or parameters are required to provide indicators for relevant information (Caswell et al. 2000). While some easily measurable traits proxy well for targeted end-use traits and are not costly to implement in wheat, other traits of interest may correlate poorly with easily measurable characteristics or be prohibitively expensive to measure. These situations increase uncertainty, and with the growing emphasis on quality requirements for specific end-uses, those levels of uncertainty are increasingly acceptable. Commercial systems are showing growing interest in, or are already transitioning towards, the use of a subset of functional traits that can be directly correlated to the quality of the desired end-use.[4]

## Challenges to Wheat Quality Improvement in the Developing World

Improving the end-use quality of wheat in developing countries presents challenges generally related to the overall structure and functioning of the wheat value chain and, more specifically, to the implementation of formal quality control systems. Achieving effective and efficient transmission of information and incentives for desired wheat quality characteristics through the wheat

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[4] The Canadian Grain Commission, responsible for wheat quality in Canada, has implemented research to develop methods to “instrumentalize” objective tests for wheat traits (Personal communication with Dr. David Hatcher, Head of Crops Section, Grains Research Laboratory, Canadian Grain Commission, July 2007.)

### Table 4. Quality control systems in selected major wheat producing countries[a]

| | Classification | Main grade criteria within classification | Administrative organization | Remarks |
|---|---|---|---|---|
| **Canada** | Prairie Wheat:<br>Can. Western Red Spring (CWRS)<br>Can. Western Hard White Spring (CWHWS)<br>Can. Western Amber Durum (CWAD)<br>Can. Western Red Winter (CWRW)<br>Can. Western Soft White Spring (CWSWS)<br>Can. Western Extra Strong (CWES)<br>Can. Prairie Spring Red (CPSR)<br>Can. Prairie Spring White (CPSW)<br>Can. Western Feed (CWF)<br><br>Eastern Wheat:<br>Can. Eastern Red (CER)<br>Can. Eastern Red Spring (CERS)<br>Can. Eastern Hard Red Winter (CEHRW)<br>Can. Eastern Soft Red Winter (CESRW)<br>Can. Eastern Amber Durum (CEAD)<br>Can. Eastern White Winter (CEWW)<br>Can. Eastern Soft White Spring (CESWS)<br>Can. Eastern Hard White Spring (CEHWS)<br>Can. Eastern Feed | Variety within class;<br>test weight;<br>vitreous kernels;<br>degree of soundness (e.g., disease);<br>foreign material and other grains;<br>wheat of other classes<br><br>The classes of CWRS, CWHWS, CWAD, and CWRW have minimum protein levels established for No. 1 grades. Protein content is reported on a 13.5% moisture basis. In effect, protein is not a grading factor for other classes/grades. | Canadian Grain Commission (CGC) recommends grades, testing and grading procedures; inspects facilities; conducts quality and other research; arbitrates disputes; certifies exports.<br><br>The Canadian Food Inspection Agency (CFIA) registers varieties and administers food safety. | • Varietal release (registration) at nationa level; variety assigned to specific class<br>• Varieties not registered are designated to the lowest grade, usually feed wheat<br>• Registration by 'merit' relative to designated standard variety<br>• Segregation by kernel visual distinguishability (KVD)<br>• Classes/grades further segregated into protein level categories<br>• Two sets of grade standards are maintained (primary and export)<br>• Export standards applied on offshore sales<br>• Less restrictive primary standards for domestic sales<br>• Increasing segregation trend<br>• Trend toward marketing by variety |
| **Australia** | Hard No. 1<br>Standard White<br>Premium White<br>Noodle Wheat<br>Soft Wheat<br>General Purpose<br>Winter Wheat<br>Feed Wheat | Approved variety for silo district<br>Moisture maximum protein<br>Test weight<br>Unmillable material maximum<br>Small foreign seeds maximum<br>Defective grains | Regulated by Australian Wheat Board (AWB) which sets variety definitions, discounts, and influences registration of varieties. | • Varieties approved by region and class<br>• Farmers required to specify varieties in affidavit upon delivery to market system<br>• Varieties grown in different states/silo districts can be relegated to different classes<br>• Feed wheat is not defined but included in general purpose class<br>• Increased segregation by end-user |
| **United States** | Durum<br>Hard Red Spring<br>Hard Red Winter<br>Soft Red Winter<br>Hard White<br>Soft White<br>Mixed Wheat | Test weight<br>Heat damaged kernels<br>Damaged kernels total<br>Foreign material<br>Shrunken & broken kernels<br>Total defects<br>Contrasting classes<br>Wheat of other classes | The Federal Grain Inspection Service (FGIS) facilitates the marketing of U.S. grain and related agricultural products through the establishment of standards for quality assessments and regulation of handling practices. It is responsible for grading and certification of all export shipments in addition to creating standards and factor limits. FGIS is housed within the Grain Inspection, Packers and Stockyards Administration (GIPSA) in the U.S. Department of Agriculture (USDA). | • Regional system of variety release<br>• Categorization of wheat by planting season and color<br>• Variety not used as a means of classification<br>• Classes do not have end-use requirements<br>• Subclass definitions and measurable wheat characteristics (e.g., protein and falling number) provided as informational items<br>• Debate over restructuring grading system to meet needs of end-users seeking high quality wheat<br>• FGIS: Mandatory Inspection only for exports |
| **France** | Blé panifiable supérieur (BPS)<br>Blé panifiable courant (BPC)<br>Blé biscuitier (BB) (Biscuit wheat)<br>Blé à autres usages (BAU) (Feed wheat) | Rewards for high protein levels<br>Bread wheat minimums specified for falling number (220 seconds), sedimentation (20 minutes), and protein content (11.5%) | | • EU standards in place for EU CAP policy purposes with additional standards at a national level<br>• Varieties used as basis of classification system and EU payments<br>• Quality of EU wheat specified by contract based on variety or groups of acceptable varieties<br>• National system of variety release<br>• Increased production/shift to medium hard varieties<br>• Inspections administered by private firms |

**Table 4. Quality control systems in selected major wheat producing countries[a] (continued)**

| | Classification | Main grade criteria within classification | Administrative organization | Remarks |
|---|---|---|---|---|
| **UK** | Group 1: Consistently good bread making quality, likely premium for protein content over 13%<br>Group 2: Bread making potential, consistent quality but not at G1 level or inconsistent quality<br>Group 3: Soft varieties for biscuit and cakes<br>Group 4: Poor quality, soft or feed wheat | | Home Grown Cereal Authority (HGCA) | Similar to France |

[a] This table draws heavily on information from Wilson (2006a).

Sources: Wilson 2006a; Mannes 2006; Official Grain Grading Guide, Canadian Grain Commission, August 2007.

value chain and by implementing systems of quality assurance will also be challenging due to limited experience and precedent, lack of necessary institutions and mechanisms, and policies in place that obstruct or contradict quality improvement efforts. Production of wheat for home and local consumption remains important, and food security has often taken precedence over quality differentiation. Increasing the potential for small and/or low income producers and consumers to benefit from wheat quality improvements poses challenges, and it is not clear which institutions, infrastructure, and policies are needed to ensure opportunities. Developing countries also face complications related to the variation in wheat producers and production conditions, as well as in the range of end-uses for wheat, which includes not only traditional products but also a growing number of non-traditional products.

## Variation in producers, growing conditions, and crop management practices

Wheat producers in developing countries are characterized by a wide range of socioeconomic traits (e.g., educational level, access to information and inputs, attitude towards new technologies, knowledge of markets). Differences in wheat growing conditions and crop management practices are similarly diverse. The interaction among producer types, environmental conditions, crop management practices, and post-harvest conditions results in potential variability in production and end-use traits. The relationship between crop management practices such as fertilizer use (especially N-supply) and end-use quality of wheat is well known. Farmers often plant wheat seed saved from the previous harvest; seed quality and replacement rates thus vary considerably. The presence of foreign material or damaged or diseased kernels, which negatively affects end-use value, is also influenced by crop management practices. Variation in grain size and shape, grain sprouting, protein content, and vitreousness is induced by environmental and management factors (Eagles et al. 2002), and the effect on end-use quality of environmental factors such as drought, heat, and disease outbreaks may be exacerbated by the economic constraints small farmers face. Though these interactions are the cause of quality-related concerns in all wheat producing countries, the problems are magnified in developing countries.

## Range of end-users, end-uses, and end-use requirements in developing countries

Both the immense diversity of wheat products consumed in developing countries and the large range of wheat end-users present challenges for the identification and standardization of end-use characteristics. The mix of subsistence and commercial end-users results in variation in processing methods (e.g., hand production, small-scale semi-mechanized or mechanized production, and large-scale commercial production) and requires different end-use characteristics and associated standards. As the existing variation in end-users and end-use requirements is not likely to disappear in the short to medium term, developing countries will need to continue to assess how best to address and prioritize these varying demands.

## Wheat value chains, quality control systems, and incentives for quality

One particular challenge for developing countries is the development, operational efficiency, and coordination of the policies, institutions, and infrastructure required for improving wheat end-use quality. Simplistically, what is required is the effective transmission of information and incentives to participants throughout the wheat value chain. National and local priorities need to be clearly communicated; institutions and infrastructure to achieve quality objectives need to be in place; and objectives and standards should be consistent with country needs and utilization patterns. Clear signals must be given to wheat scientists and seed producers as to the quality they should pursue in their breeding and seed multiplication programs, and institutional incentives should be in place to promote development of varieties with the desired qualities. To participate in markets, wheat producers in developing countries must often satisfy their own consumption needs first; however, they also require information and incentives to make appropriate variety choices, given end-user demands. Traders, processors, and other end-users need assurances that they have basic, dependable information on the qualitative characteristics of the wheat they purchase, that there is reasonable consistency in wheat characteristics across regions and time, and that supply will be adequate to satisfy their demands.

Informal quality control systems seem to be functioning to a certain degree at the local level in many developing countries, but due to the informal nature of these systems, the probability of breakdowns in transmission of information on quality standards and incentives increases as the distance and number of people involved increase. To improve the effectiveness of quality control systems, appropriate and feasible standards for the range of end-uses in a country need to be identified and implemented, and variety-based or other classification systems need to be put in place. Also important is the establishment of clear operational objectives that are feasible and manageable in regulatory and commercial terms, including clarity on who manages the system.

Infrastructural requirements include facilities that enable wheat segregation by quality, as well as coordination of handling, transportation, and storage functions. Segregation and grading, supported by testing, inspection, and certification, are all essential components of quality control and trading arrangements. The handling and transportation system must be compatible with maintaining the appropriate segregation through to the end-user. If segregation standards and practices

### Box 1. Segregation and Identity Preservation

The segregation of wheat means that wheat with like characteristics is separated from wheat with non-like characteristics, usually as part of the grading process, and [that] once separated, it is maintained separately in the marketing chain. The term is sometimes used as similar or equivalent to the term identity preservation (IP). However, IP requires segregation as well as preservation of the identity from its origin throughout the chain. IP is sometimes viewed as strictly a commercial contracting arrangement associated with 'trace back' capability. It may be motivated by very specific quality traits or traits outside the grading system, and may be used as a mechanism for ensuring food safety. Segregation and IP, therefore, can be viewed as part of a continuum of steps in accomplishing quality objectives related to wheat demand and supply. Administration by a government or near-government agency is often, but not necessarily involved. Segregation can be carried out based on varieties or on their intrinsic end-use characteristics; varieties may also be grouped into "classes" and class end-use used as the grading criterion (Canada). In France, end-use is the sole factor for grouping, and in the United States wheat type (hard red spring, hard red winter, durum, etc.) is the class determinant.

**Table 5. Current and proposed wheat classification systems in selected wheat producing countries**

| | Classification | Main grade criteria within classification | Remarks |
|---|---|---|---|
| **Argentina** | Group 1: Corrector wheat (industrial breadmaking)<br>Group 2: Wheat for Argentina traditional breadmaking (> 8 hours of fermentation time)<br>Group 3: Wheat for direct breakmaking (< 8 hours of fermentation time) | Test weight, damaged crop, foreign matter, protein content | Soft wheat, while previously disallowed, is now allowed, but pre-release testing requirements must be met |
| **Mexico** | Quality Group I (F): strong and extensible gluten for mechanized breadmaking industry<br>Quality Group II (M): medium-strong and extensible gluten for semi-mechanized breadmaking industry (baguette, flour tortilla), regional sweet rolls, flour noodles<br>Quality Group III (S): weak and extensible gluten for cookies<br>Quality Group IV (T): medium strong and inextensible gluten for regional breads, cakes, pastry, home-made flour tortillas (not for breadmaking)<br>Quality Group V (C): durum wheat for alimentary pasta | Test weight, damaged crop, foreign matter, moisture | Name of variety is followed by a suffix indicating its quality group and year of release. Example: Sonora F 64.<br>Group 4 is now no longer available. Breeders do not release this type of wheat.<br>Blending varieties of distinct quality groups is common to achieve the specific end use quality required. |
| **Brazil** | Trigo melhorado (improved) for pasta, mechanized breadmaking industry, alimentary pasta, corrector in blending<br>Trigo pão (bread type) for semi-mechanized breadmaking industry, baguette type products, pasta, homemade breads<br>Trigo brando (soft wheat) for sweet breads, cakes, cookies, homemade breads<br>Trigo para outros usos (utility wheat) for animal feed, industrial use | | |
| **China** | Hard white winter wheat: white kernel >90%, kernel vitreousness >70%<br>Hard white spring wheat: white kernel>90%, kernel vitreousness >70%<br>Soft white winter wheat: white kernel>90%, opaque kernel>70%<br>Soft white spring wheat: white kernel>90%, opaque kernel>70%<br>Hard red winter wheat: red kernel>90%, kernel vitreousness kernel>70%<br>Hard red spring wheat: red kernel>90%, kernel vitreousness >70%<br>Soft red winter wheat: red kernel>90%, opaque kernel>70%,<br>Soft red spring wheat: red kernel>90%, opaque kernel>70%<br>Mixed wheat: wheat that cannot otherwise be classified<br>High quality wheat specification:<br>High Quality Hard Wheat (Strong Gluten) Grade 1<br>High Quality Hard Wheat (Strong Gluten) Grade 2<br>High Quality Soft Wheat (Weak Gluten)<br>Ordinary Wheat | Test weight, broken kernels, moisture content, foreign material, color and smell | Standards for quality were revised in 1999. Standards for grade 3 and above became know as "ordinary wheat" and additional standards, including protein content, falling number, wet gluten content, stability and hong pei (a baking quality index), were developed to identify three types of "high-quality wheat." The standard for classification as non-mixed wheat was raised to 90 percent of kernels from 70 percent for "ordinary wheat." For high-quality hard wheat grades 1 and 2, minimum wet gluten is 35 and 32 percent, and stability is minimum 10 and 7 minutes. The baking quality index (hong pei) must be at least 80 out of a possible 100 for high-quality hard wheat. For high-quality soft wheat, the standards are at most 11.5 percent protein, 22 percent wet gluten and 2.5 seconds stability time. Hong pei is not measured for high-quality soft wheat. All three high-quality wheat categories must have a falling number above 300 seconds (Lohmar et al. 2007) |
| **India** | Current classification system for bread wheat based on agro-ecological zones and management conditions (e.g., timely and late sown in irrigated areas and rainfed areas) | | |

**Table 5. Current and proposed wheat classification systems in selected wheat producing countries (continued)**

| | Classification | Main grade criteria within classification | Remarks |
|---|---|---|---|
| **India** | Proposed classification system:<br>Indian Hard White/Amber Medium size; plump; medium hard; protein >12%; strong gluten | | |
| | Uses: pan type bread, hamburger bread, pita bread, spaghetti, porridge | | |
| | Indian Medium Hard White/Amber. Long; plump; medium hard; protein 10-12%; medium strong and slightly extensible gluten; low PPO activity<br>Uses: hearth breads; flat breads of India (chapati, paratha, nan) and WANA (Arab, nan, tandori, etc.); flour noodles; crackers; sweet dishes | | |
| | Indian Soft White/Red. Medium size, protein <10%; low alkaline water retention capacity<br>Uses: biscuits, crackers, cakes, pastry | | |
| | Indian Durum Wheat. Vitreous; high yellow pigment; protein >12%<br>Uses: pasta, sweet and salty porridge, chapati, traditional sweet dishes | | |
| **Turkey** | I-DURUM WHEAT<br>1-Durum Wheat<br>II-BREAD WHEAT<br>Anadolu Hard White<br>Anadolu Hard Red<br>Medium Hard Red<br>Medium Hard White<br>Others (Red-White) | | |

Sources: Cunitberti and Otamendi (2005); Ministério da Agricultura, Pecuária e Abastecimento (Instrução Normativa no 7, de 15 de agosto de 2001. Norma de identidade e qualidade do trigo. Diário Oficial [da] República Federativa do Brasil, Brasília, DF, n. 160-E, p. 33-35, 21 ago. 2001. Seção 1); Gupta undated; Joshi (pers. comm.); He (pers. comm); Lohmar et al. (2007).

(supported by research and quality-testing) are not effective, information asymmetries and uncertainty will persist within the wheat value chain and may well obstruct initiatives to improve wheat quality.

Many developing countries are implementing changes to address the increased emphasis on specific quality attributes in wheat end-use and trade. Standards for end-use quality and wheat classes have been established in Argentina, Brazil, Mexico, Chile, and Turkey to promote quality improvement and facilitate trade based on quality, but many have yet to be fully implemented. Table 5 provides information on current and proposed classification systems in some of these countries. They are the result of trade interests and goals, as well as a means of reducing inconsistencies in the quality delivered (e.g., the mixing of varieties with different qualities, known as commingling) and pricing uncertainties (J.L. Fuente-Pouchat, AIHC, Mexico, pers. comm.). Initiatives to establish classes and standards are ongoing in India, where quality requirements of common wheat products and quality characterization of currently cultivated wheat varieties are being investigated (Gupta undated). In recent years, China has begun to emphasize wheat quality improvement as an objective for its wheat industry, and the need to improve national standards and classifications for end-use quality and to address quality inconsistency across years and locations has been pointed out (He 2006; Wang et al. 2004). Turkey, where improved quality has become a top priority for wheat improvement, is an example of producers' quick response to changes in the value chain. The introduction of a grading system in which significant price differences are closely linked to quality classes and grain purity has had a major impact on farmers' choice of varieties and weed control efforts (Braun, pers. comm.)

Ultimately, the priority given to wheat quality is reflected by the actual decisions and actions of producers and end-users (Brennan 1997). Accurate market signals about quality are crucial to induce the appropriate response from growers or others in the system. A quality control system in which operating costs and the costs of measuring end-use traits are greater than their expected benefits will not be valued in a market environment. In such a situation, expected premiums or income related to end use-traits may not materialize, and efforts/expectations to influence producers to supply wheat with specific end-use traits through price incentives may not be effective. Yet incentives of some kind are a key part of effecting changes in behavior. Without incentives to attain quality targets (by premiums within grades or some other type of reward based on delivered end-use quality), the message to breeders and other researchers is that there is no advantage in developing varieties with better than minimum quality, and producers have no incentive to achieve more than the minimum standard (Brennan 1997). The roles of public and private institutions in the quality control system and within the broader wheat value chain thus need to be considered. How to finance the implementation and administration of a formal quality control system remains a question in many countries. What will be the costs, who will pay for pay for them, and what incentives are needed?

Uncertainty about the value of end-use attributes and differences between producers and end-users in the valuation of end-use attributes continue to be an issue in commercialized wheat producing countries, due to imperfect correlations between inherent wheat characteristics and functional (end-user) characteristics. The absence of market premiums or discounts that are linked to functional characteristics and the variability over time of the premiums/discounts that do currently exist also contribute to the uncertainty and differences in valuation (Wilson 2006b). Rather than expectations of greater income, it may be that assurances of end-use quality through the implementation of standards and grades will be a prerequisite for future market entry. With globalization and industrialized processing, the industry will prioritize the purchase of wheat having the required quality, and it will more than likely not be restricted to local procurement.

One additional issue of relevance for developing countries is how to ensure distribution of some of the benefits from wheat quality improvements to small farmers, who face such constraints as limited access to inputs and technologies, lack of information on wheat quality attributes, and high transaction costs to access information on quality standards and markets. These concerns are similar to those discussed in general for smallholder participation in high value agriculture. The role of innovative institutions and appropriate infrastructure is critical, particularly to reduce risks and transaction costs and promote appropriate compliance measures for standards (Joshi et al. 2007).

## Implications for Wheat Research

In the short-to-medium term, the majority of wheat in developing countries will likely continue to be consumed in the form of the same products as it is today. What is expected to be a significant change, however, is the increasingly industrialized production of those wheat products. Wheat producers in developing countries will need to be able to meet the end-use requirements of the wheat processing industry, whose demand for wheat with defined and consistent quality traits will be one of the most, if not the most, important driver for wheat quality improvement in the coming two decades.

Meeting quality characteristics and, equally significant, delivering wheat with consistent quality, will become more and more important in developing countries. For many NARS breeders, improving wheat quality may assume an even higher priority than improving wheat yields and breeding for tolerance/

resistance to abiotic and biotic stresses. An additional objective—on top of the already multiple objectives for wheat improvement—implies tradeoffs in the potential gains in one trait against gains in others. Exactly where the improvement of wheat end-use quality (along with the resources allocated to it) falls within the priorities of a wheat national program is a first order decision; a second order decision involves which types of end-use quality to improve and the means of doing it.

The inverse relationship between grain yield and grain protein content has long presented a challenge to improving or maintaining grain quality. The recent identification of genes that elevate protein content may enable the use of marker-assisted selection (MAS) to address undesirable correlations between grain yield and grain protein concentration, and to develop plants that efficiently produce and partition carbohydrates to grain yield (De Pauw et al. 2007). However, high protein content does not guarantee good end-use quality for breadmaking, nor is it necessarily the most relevant quality trait for many of the wheat products consumed in developing countries. One of the main factors determining wheat end-use quality is gluten, which gives dough its visco-elastic properties (Peña et al. 2002,). Grain hardness is another major component of wheat quality, and changing from soft to hard wheat has a greater effect on quality than either protein quality or quantity (Manes 2006). Grain hardness is also a major factor in market classification. Hard wheat produces flours with much higher water absorption than soft wheat, and it is largely this difference in water absorption capacity that makes soft wheat suitable for cookies and sweet breads, and hard wheat suitable for bread making. Protein content is the only quality trait for which there is evidence of a negative correlation with yield. There is as yet no evidence of a negative yield effect across wheat classes differentiated by grain hardness, and abundant evidence indicates that it is possible to improve protein quality at given protein levels (Manes 2006). Significantly, the type of classification system used, as well as the specific end-use, are key determinants of whether or not quality is negatively correlated with yield. Market structure thus plays an important role in defining the focus of wheat research and breeder strategies for combining improved yield and end-use quality (Manes 2006).

To improve end-use quality, wheat scientists must know which relevant end-use attributes to focus their efforts on and the target range for improvement associated with each end-use trait. For this reason, the identification of traits inherent in wheat that are directly correlated with desired end-use characteristics is becoming increasingly important. The extent to which genetic improvement will be possible is a function of the available or potential genetic variability in the breeding materials and of the knowledge required to incorporate the variability into new germplasm. Knowledge of functional quality-related characteristics and desirable/undesirable quality-related genes or allelic combinations allows breeders to plan crosses that are more likely to generate desirable wheat quality types (Peña et al. 2002). In breeding for end-use quality, at least part of the various genetically-controlled traits (e.g., grain size, color, and hardness; storage proteins, starch, and enzymatic activity) must be addressed. A better understanding of the influence of genetic interactions with environmental conditions (e.g., heat, drought, high humidity) and the effects of crop management practices on the expression of traits of interest will also be important in improving quality consistency. Variations in grain size and shape, kernel vitreousness, grain sprouting, and protein content can all be environmentally and management induced (Eagles et al. 2002).

Efficiency in breeding for improved quality can be enhanced by using quality-testing methodologies such as MAS and near-infrared spectroscopy (NIRS).

Rapid, high-throughput screening tests that are readily available and affordable are essential to ensure the existence of desired quality characteristics during the breeding process and to estimate physical, compositional, and functional grain and flour factors closely associated with milling and wheat processing quality. NIRS is already being used for traits including grain hardness; protein content; flour color for noodles and semolina yellowness for durum wheat products; and sedimentation, an indirect measurement of gluten quality. Calibrations are underway for more exact grain color, flour color, dough rheology parameters (e.g., dough development time), gluten strength, and starch and amylopectin content associated with starch pasting for good noodle quality. Determination of allelic variants for all critical protein quality traits and the use of MAS and NIRS are routinely applied at CIMMYT as part of the set of essential tools and strategies to improve yield, disease resistance, and quality, and to reduce yield-quality penalties as much as possible. In its wheat improvement program, CIMMYT continues to prioritize the supply of core quality traits for bread and durum wheat in germplasm distributed to national programs and ensure the availability of genetic diversity for niche traits.

If expected trends in end-use quality differentiation in wheat continue, it will be the wheat scientists in developing countries who will be responsible for generating varieties that satisfy specific end-uses and the needs of the range of household and industrial end-users unique to their own countries. Efforts are already well underway in many countries to establish quality requirements, standards, and measurements for specific end-uses, and to characterize the quality traits of current varieties and breeding materials. It is also clear that efforts to improve end-use quality cannot succeed if undertaken in isolation from other developments within the wheat value chain. Continuous examination and assessment of investments in germplasm improvement, other related research that considers the stability and robustness of market and price opportunities, and progress in developing the necessary policies, institutions, and infrastructure will also be essential.

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# Improved Discovery and Utilization of New Traits for Breeding

**J.H. Crouch, T.S. Payne, S. Dreisigacker, H. Wu, and H.-J. Braun**

## Introduction

Wheat productivity has undergone a spectacular rise in many countries over the last half century. Average global wheat yields have risen from about 1 t/ha in the 1950s to nearly 3 t/ha at the turn of the last century. Initial increases were due to the introduction and dissemination of high-yielding, fertilizer-responsive semidwarf varieties, generally known as the Green Revolution varieties. The introduction of dwarfing genes and subsequent improvements in harvest index increased grain yield, particularly by allowing farmers to apply higher rates of nitrogen fertilizer without fear of crop lodging. In rainfed and semiarid areas, partly due to the wider range of constraints that afflict these cropping systems, adoption of improved cultivars has been slower; still, nearly three-quarters of these areas are sown to semidwarf cultivars. Achieving similar productivity increases in resource-poor rainfed areas will require progress in many complex traits, including drought tolerance and nutrient use efficiency. Meanwhile, sustaining productivity increases in Green Revolution areas is under threat due to the decreasing availability of water for irrigation. Thus, water use efficiency must be improved to provide new, high-yielding varieties that make the best use of supplementary irrigation. Looking ahead, the effects of climate change will increase the need for cultivars with heat and flooding tolerance, while also influencing pest and disease pressures in diverse ways.

Breeding gains for tolerance to abiotic stresses have been tangible, albeit incremental, but nevertheless demonstrate that the problem is tractable to a genetic approach. Progress is constrained by the available genetic variability and the complexity of genetically improving crop adaptation. Significant progress has recently been made using synthetic wheat lines to introgress resistance/tolerance to multiple stresses from wild species. Although these breeding systems are slow and time-consuming in comparison to mainstream breeding, they are often the only way to access new sources of genetic variation for important agronomic traits. Thus, the current challenge is to create more efficient methods for rapidly accessing the best sources of genetic variation for specific target traits and to develop new tools that will improve the pace and efficiency of manipulating and utilizing beneficial genetic variation in breeding programs.

Finally, there is no doubt that grain quality will become an increasingly important issue in all production areas. For breeding programs to become highly responsive to the associated market demands will require a range of new tools and breeding systems. Investments in these areas are high and must be carefully focused, but potential payoffs are also high, particularly as wheat producers attempt to enter new added-value markers. Similarly, local or traditional grain quality is extremely important for smallholders who produce wheat mainly for home consumption, but it is difficult to combine good grain quality with high productivity in abiotic stress-prone production systems; this is a frequent constraint to the adoption of new varieties.

The impact of new technologies on wheat breeding is likely in seven main areas:
(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.

## Trait Discovery

### Dynamic core collection selectors

Representative entry points to large germplasm bank collections, core collections are of manageable size and allow researchers, breeders, and trait specialists to carry out replicated, multilocational precision phenotyping and effective screening (Franco et al. 2006). In this way, core subsets have facilitated the increased utilization of genetic resources stored in germplasm collections, particularly for crop species with moderately sized collections of up to 30,000 accessions. Core collections have also been valuable for genetic diversity studies, association genetics, and preliminary allele-mining initiatives (Balfourier et al. 2007). However, this approach has had less impact on crop species with larger collections and/or collections where a large portion of the diversity is spread over several species or genebanks. In addition, the definition of static subsets inevitably does not best serve all potential end-users, irrespective of the size of the main collection, and may become outdated as new data become available. Thus, there is a need for new computer tools that can provide a more tailored sampling, fulfilling the needs of the end-user while providing a balanced and diverse set of germplasm using all data available at that time. Generating a robust user-friendly tool for this purpose will require advances in biometrics and software development. A tool that facilitates designating dynamic subsets based on need and provides direct access to all available data will substantially increase the efficiency of genetic resource utilization across all crop species. If several genebanks for the same crop agree to pursue a similar approach, then web-services or similar tools may enable the end-user to create a subset across genebanks. This type of tool will dramatically increase the efficiency and scope of use of genetic resources, which will, in turn, substantially increase the impact of wild species in wheat breeding.

### Gene identification

The understanding of and ability to manipulate the underlying genetic control of complex characters such as yield potential and tolerance to abiotic stresses is essential to future plant breeding gains. In contrast, the situation for biotic stresses (pest and disease resistance) is often genetically much simpler. Researchers are therefore devising novel strategies for in-depth structural and functional analysis of the wheat genome despite its large size and complex polyploid nature. Wheat has been a model crop for cytogenetic studies for the past three-quarters of a century, which has resulted in a plethora of cytogenetic stocks of considerable value for locating target genes (Jiang and Gill 2006). A global public access database of wheat expressed sequence tags (ESTs), currently the largest of any crop, is growing rapidly. This is proving highly valuable in analyzing the expression of specific genes of agronomic importance, mapping wild sources of such genes, and developing gene-based markers for molecular breeding. ESTs are particularly amenable to the development of single nucleotide polymorphism (SNP) markers, highly valued due to their potential for automation in high-throughput genotyping platforms.

Traditional mapping of quantitative trait loci (QTL) using genetic populations generated by crossing two genotypes contrasting for a trait of interest has been useful in establishing the putative genomic location of the genes contributing to a target trait, and for partitioning variation into single Mendelian genetic factors. Although highly precise, this approach can only elucidate the relative effects of the two alleles contributed by the two parental genotypes; furthermore, it takes many years to complete the entire process. For complex traits, the resultant markers are often population-dependent and thus show a substantial level of redundancy when used in breeding populations. In contrast, association analysis has the potential to distinguish most of the favorable alleles at a locus at relatively low cost, and may provide markers with a broader predictive power and better transferability among different populations without the need for generating specific genetic populations (Buckler and Thornsberry 2002). Although currently this approach is generally applied to diverse germplasm, the expectation is that it will soon be possible to use it in breeding populations that are well characterized phenotypically. This will have a dramatic effect on the pace and efficiency of identifying marker-trait associations and, consequently, on the impact and scope of marker-assisted selection (MAS).

## Allele mining

Once genes have been identified that affect a trait of interest, allele mining can be used to find more variation at the DNA sequence level that may cause different phenotypic expressions of the trait. These new alleles can be used to improve the level of expression of the trait (an even better form of the trait); the timing of expression (only when needed, to avoid stressing the plant with unnecessary expression); the tissue in which the trait is expressed; and other variants that can make the plant more productive or adapted under biotic or abiotic stress conditions. Two main approaches have been developed for allele mining: re-sequencing and ecotilling. As sequencing becomes significantly cheaper through new methods, it will be possible to routinely mine germplasm collections for allelic variation in a target gene of interest. This approach will be particularly powerful for traits where all the underlying genes have been isolated and validated in model species. Databases of allelic patterns and corresponding phenotypes will rapidly build up over the next five years. It will then be possible to rely on genomic analysis to identify germplasm subsets with allelic variation most likely to be beneficial for the target trait, thereby facilitating precision phenotype screening of the minimum number of accessions. This will have a dramatic effect on the scale and efficiency of use of germplasm collections.

## Precision screening

The quality of phenotyping is the single largest constraint to many areas of research and breeding. Screening wild species or segregating early generation breeding materials for complex traits is particularly fraught with problems. Thus, there will be increasing emphasis on screening of physiological parameters associated with the trait of interest in highly controlled, well designed experiments. This will enable much more efficient mining of useful variation, but will require a substantial increase in physiology research to identify parameters with robust relationships between screening experiments and trait performance under field conditions. In addition, there will be increasing emphasis on creating specific genetic populations that simplify the genetic dissection process (for example, removing the confounding effect of phenology when attempting to dissect drought tolerance). This will significantly improve the accuracy and precision of genetic mapping studies. However, increased research on whole-plant physiology modeling will be required to ensure that the dissected components can be effectively reconstructed in a design-led product development manner. It is clear that major private sector firms are already moving towards this for commodities of significant economic value. Thus, similar achievements are expected in wheat within the next 10 years.

## Improved Efficiency When Using Exotic Germplasm in Wheat Breeding

As wheat breeders work to develop new varieties combining improved tolerance to abiotic stresses with increased resistance to pests and diseases as well as desired quality characteristics, they need greater access to novel genetic variation for these traits. Wheat landraces and wild related species possess many novel genes and can be readily crossed with durum wheat and bread wheat breeding lines. However, the speed and efficiency of current breeding systems need to be drastically improved, particularly to become more predictive. Once this is achieved, wild species will have a much more dramatic impact on wheat breeding.

### Synthetic wheat

Tetraploid (durum) wheat and hexaploid (bread) wheat can be resynthesized from their progenitor species. This allows making artificial crosses that capture full taxonomic diversity, similar to the few rare chance events that occurred during wheat's evolutionary process. Creating synthetic wheat lines is much easier than performing conventional interspecific hybridization, and the resulting germplasm is much more readily used in mainstream breeding programs, although it still requires several backcrosses to remove undesirable agronomic traits such as glume tenacity, shattering, seed dormancy, tall stature, and late maturity. The use of synthetic lines in CIMMYT's rainfed wheat breeding program has facilitated a dramatic increase in drought tolerance. This type of material is expected to have similar impacts on other abiotic stress tolerances as well as pest and disease resistances over the next 10 years. In China a new cultivar has already been released whose disease resistance originated from a CIMMYT synthetic wheat line. In addition, field tests have confirmed that synthetic lines may be good sources for improving photosynthetic rate, salt tolerance, grain micronutrient content, resistance to Karnal bunt and helminthosporium leaf blight, and kernel weight. A large proportion of crosses in CIMMYT's breeding programs now include a synthetic line or derivative thereof (see Figure 1 for further details).

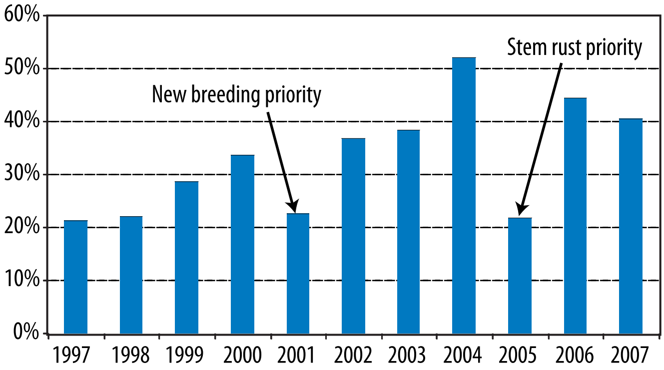

**Figure 1. Percentage of crosses with a synthetic wheat hybrid line in one of the parental pedigrees (CIMMYT rainfed wheat breeding program, 1997-2007).**

### Translocation lines

Many alien species (such as *Aegilops*, *Agropyron*, *Haynaldia*, *Secale*, and *Thinopyrum*) are known to be good sources of disease resistance and biotic stress tolerance. They can be used in wheat breeding programs through the formation of translocation lines (chromosome segment substitution lines). Unfortunately, the genes that confer resistance/tolerance are often linked to deleterious traits, including reduced yield or poor end-use quality; a situation known as linkage drag. Methodologies that break this linkage drag would have dramatic impact on the breeding of many traits for which beneficial genes have been identified in wild species.

Recombination between chromosomes of cultivated wheat and *Thinopyrum* and *Aegilops* species has been induced by using mutants or through transient genetic suppression (such as RNAi) of the *Ph1* gene. However, the recent cloning of the *Ph1* gene has opened the way for a much more precise and efficient approach based on the use of a chemical treatment system for temporarily switching *Ph1* off at the most convenient stage of the breeding process. To design the most efficient breeding system using *Ph1* suppression will require DNA markers that are very close to the target gene, markers in close flanking proximity to the same gene, and markers evenly distributed across the rest of the chromosome. It may be necessary to carry out this germplasm enhancement step in a durum wheat background and then use the tetraploid product in a synthetic hexaploid bread wheat. This would have the advantage that the increased recombination would not break up blocks of genes that have been fixed through concerted breeding efforts and have become an essential foundation of modern wheat cultivars. This genomics-assisted germplasm enhancement system is likely to be routine within the next five years.

### Optimizing germplasm enhancement systems

As part of ongoing efforts to assess the contributions of intermediate products to the development of new cultivars, CIMMYT is generating methodologies to calculate the contribution and cost-effectiveness of utilizing synthetic lines to develop wheat cultivars for various target environments. Analyses are currently underway to determine the relative success rates associated with different subsets of wheat lines that entered the rainfed breeding program at the same time. By tracing the progress of lines derived from these sources (from their initial appearance in a crossing block to their selection for inclusion in an international yield trial), CIMMYT can gain a better perspective on which breeding strategies, including the use of synthetic lines, have been most successful. Based on modeling of this data, simulations will be generated that can form the basis of tools to support breeding decisions and help design the most efficient breeding system for any target trait or cropping system. This approach will facilitate priority setting when investing in various breeding technologies or approaches. It is expected that within 10 years, wheat breeders will routinely use decision-support tools that optimize not only genetic effects but also economic implications. This will bring a new level of design-led efficiency to wheat breeding.

## Genetic Transformation

Transgenic crops are spreading more rapidly than any other agricultural technology in history, which suggests that many farmers perceive important advantages to growing them. Genetically modified (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. Developing countries now account for 38% of the area sown to GM crops worldwide (Raney 2006). Genetically modified crops, notably maize, soybean, cotton, and canola, now account for more than 250 million ha of commercial crop production across 22 countries (James 2006), leading to an estimated increase in farm income of more than US$ 25 billion (Brookes and Barfoot 2006). 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. As the extent of GM crop cultivation and consumption increases, consumers and policy makers across the world should become increasingly comfortable with this type of technology.

Although the first successful transformation of wheat was reported in 1992, GM wheat has not yet been approved for commercial production in any country; however, controlled field trials of transgenic wheat have been approved in several countries. If the public accepts GM wheat, the benefits for producers and consumers could be high—for example, reduced prices due to more stable production despite drought and heat stress, improved grain quality due to enhanced nutrient value, and health benefits such as reduced risk of mycotoxin contamination associated with infection by fusarium head blight.

There are claims that the price of GM cultivars would be beyond the reach of resource-poor farmers. However, experiences with hybrid maize, sorghum, and millet, plus GM cotton in Africa and Asia, have shown that significant numbers of low-income farmers are willing to invest in seed of new cultivars providing there is high probability of stable increases in productivity and/or net profit. Nevertheless, the potential economic and health benefits of this new generation of breeding products are still a cause for concern for many consumers, who worry about their impact on the environment or more general moral and biosafety issues. In this respect, CIMMYT makes no judgment but instead focuses on developing a range of solutions using different approaches to provide end-users and consumers with choices.

## Drought and heat tolerance

Given that GM wheat with increased drought tolerance would reduce the vulnerability and risk of poor farmers in drought prone areas, CIMMYT has been testing the effect of the DREB gene and other regulatory and functional genes on enhancing water use efficiency and drought tolerance. Similar activities are further advanced in maize, particularly in the private sector, and suggest that this approach can be highly successful (Nelson et al. 2007); so much so, that there is a significant possibility that drought tolerant GM maize will in the future replace wheat in some areas, if parallel advancements are not achieved in wheat. The combination of drought and heat stress occurs in large production areas and has considerable impact on yield (Barnabas et al. 2008). Substantial public and private investments have been made in identifying useful genes for these traits, and have already led to impressive results in maize (Nelson et al. 2007). This type of development is likely to have significant impact on improving wheat productivity in semi-arid and rainfed production systems across the developing world within the next 10 to 20 years.

## Novel quality traits

Surveys suggest that consumers are more likely to accept GM wheat if the improved traits significantly enhance product quality; e.g., increased nutrient concentration, and pharmaceutical and health benefits. It is important to engage the food industry's support for GM wheat, as social acceptance issues have caused the processing industry to adopt a highly conservative approach to this issue. It is likely that GM wheat will be accepted in OECD countries, where efficient segregation systems (on the supply side) and labeling systems (on the demand side) are well developed. Meanwhile, the first countries to switch to GM wheat will most probably be emerging economies in need of high domestic yields to offset increasingly expensive wheat imports.

## Hybrid technology

Half a century of research on hybrid wheat has yet to produce compelling results, partly due to the relatively low yield advantage of hybrid varieties. Nevertheless, hybrid wheat has been commercialized in a few countries (France, Australia, USA, South Africa, China, and India), while hybrid maize and rice have become great successes among resource-poor farmers in many countries; initial indications suggest that the same will be true for wheat. Cytoplasmic male sterility (cms) systems have had dramatic impact on hybrid seed production in rice, sorghum, sunflower, tobacco, and many vegetable crops. There appear to be real opportunities for developing transgenic cms systems for many other crops, including wheat (Pelletier and Budar 2007). All natural cms systems appear to be conferred by mitochondrial genes that would require plastid transformation, protoplast fusion, or the identification of nuclear genes capable of controlling organelle genes to enable transfer of the cms trait to wheat genotypes. Considerable on-going research in this area has already yielded promising results in model systems (Li et al. 2007).

## Improved Breeding Methods

### Marker-assisted selection (MAS)

If the gains in wheat yields are to be maintained or even increased, our understanding and ability to manipulate the underlying genes for complex characters such as yield potential, tolerance to abiotic stresses, root health factors, and polygenic disease resistance must be improved (Snape et al. 2007). The search for quantitative trait loci (QTLs) influencing these traits has been confounded by poor quality phenotypic data, the inappropriate nature and size of mapping populations, and/or the inadequate density of molecular markers. Genotype x year interactions are often the single largest source of error in analyses of multi-environment trials. Therefore, many QTLs are not observed to be consistently expressed across seasons, locations, or populations. Large-effect QTLs with good stability across cropping environments and diverse genetic backgrounds are rare, and novel approaches are needed to improve the efficiency of identifying them.

The practical value of a marker depends on how successfully it can be integrated into a breeding program, and how easily it can be applied on a large scale in modern breeding programs. Marker systems such as RFLPs or AFLPs do not meet this criterion due to their laborious application. Thus, molecular breeding programs will focus on PCR-based assay systems such as STS, SSR, and SNP markers. For maximum throughput potential with minimum unit costs, SNP markers will eventually be used on all crops. However, the generation of large numbers of SNP markers for molecular breeding of wheat has been highly constrained due to the low levels of polymorphism in wheat breeding programs. Nevertheless, this problem is expected to be completely resolved within the next five years.

### Molecular breeding

The large-scale use of markers in wheat breeding is also currently limited by a lack of markers for complex traits and the absence of low-cost, high-throughput genotyping platforms appropriate to the needs of wheat molecular breeding. Marker detection through currently available capillary electrophoresis systems offers significant incremental advances in throughput and unit costs, but dramatic progress will have to await appropriate SNP-based systems. Large-scale EST sequencing, BAC-end sequencing, and whole-genome sequencing projects will undoubtedly lead to the development of a large number of SNP gene-based markers over the next five years. These SNP markers will be an important source of gene-based markers that are good candidates for molecular breeding and allele mining. There are several potential high-throughput platforms for large-scale, low-cost simultaneous genotyping of fewer than 100 SNP markers, which may be appropriate for the interim generation of wheat molecular breeding applications in the next five years. However, within the next 10 years, micro-array-based genotyping systems are expected to provide at least a 10-fold increase in throughput potential, plus great reductions in unit costs.

### Association genetics and computer systems

The current challenge is to establish a close, iterative collaboration between molecular biologists and wheat breeders such that the results of whole-genome scanning and association genetics can be rationalized and deployed within wheat breeding programs. These techniques have the potential to substantially improve parent selection for crossing, the rate of genetic gain, and the time taken to develop new cultivars (Bresghello and Sorrells 2006). However, this will require substantial advances in facilitating computer systems. Advanced wheat breeding lines have been distributed annually by CIMMYT (and its precursor organization) to up to 150 global locations for nearly half century. Yield and agronomic data have been collected from these trials and returned to CIMMYT for analysis and collation in public access databases. Seed of all these materials has been conserved in the CIMMYT gene bank and used for genotyping and the successful pilot testing of association analysis using wheat breeding materials for a diverse range of agronomic traits (Crossa et al. 2007). This provides more robust and effective marker-trait associations than those developed through more conventional approaches. More importantly, as opposed to genetic populations, it allows integrating the development and validation of new markers into breeding programs. This will be particularly important for MAS of complex traits such as drought tolerance and nutrient use efficiency, polygenic pest and disease resistance, and grain quality traits. However, this will require substantial advances in computer decision-support tools. Once available, these tools will help breeders select the best parental genotypes, optimize the breeding system, and design the most appropriate selection systems. This will have a dramatic effect on the impact of MAS and on the rates of adoption of MAS technologies.

## Molecular breeding with transgenic lines

Although GM forms of wheat are not currently in commercial use, on-going gene discovery projects are generating a stream of candidate genes with potential for future transformation programs. When the cultivar with the best agronomic type is not the most receptive to transformation, it is possible to transform a more receptive cultivar and then introgress the gene into the target background using diagnostic markers for the transgene. This type of MAS-aided line conversion for a range of desired backgrounds is routinely practiced in the private sector for all crops where GM cultivars have become commonplace. Thus, this is expected to become an important tool for future wheat breeding.

## Breeding with double haploid lines

Double haploid lines have been used, particularly in the private sector, to improve the speed and precision of breeding many crops including wheat. Double haploid systems allow rapid generation of homozygous lines, which improves breeding efficiency by reducing the amount of time required to develop fixed lines. Wheat double haploids can be generated through anther or microspore culture or by using a maize pollen induction system (very labor intensive). In commercial wheat breeding programs, thousands or even tens of thousands of double haploid lines are produced as part of the annual breeding process. Some wheat breeding programs have completely converted to double haploid-based breeding systems, especially winter wheat programs where time-saving is greatest. In addition, the most technology-driven breeding programs have been the fastest to adopt double haploid breeding systems, as they facilitate integrating MAS into breeding programs and conducting mapping and genetic studies within breeding populations. For CIMMYT's spring wheat program, which runs two complete field selection cycles per year, the time advantages of double haploids are less obvious.

However, double haploid breeding systems have substantial potential advantages beyond saving time and easing logistics. Double haploids allow the breeder to select among fixed lines at the maximum level of genetic variability, viz., the first generation after crossing. In conventional breeding programs, early generation materials must be selected within families of genotypes evaluated in relatively few replications and locations. Double haploid-based breeding systems should allow breeders to select elite genotypes that may have been missed during conventional breeding. However, this may not hold for complex traits such as adult plant resistance to cereal rusts (based on many minor genes, each with small additive effects); in those cases, only when three to five genes are combined is an acceptable level resistance achieved. In the absence of markers for such traits, the frequency of these genes can be sequentially increased by field selecting the $F_2$ to $F_5$ generations. For double haploids to be effective in these cases, it is necessary to use very large populations (to have a reasonable probability of identifying segregants with all the necessary genes) or to pursue more than one cycle of double haploids. In these cases, the cost-benefit ratio is less obvious unless field screening for these traits is highly inefficient. Thus, the extent to which double haploids will be beneficial in global wheat breeding programs will need to be determined through empirical studies. Nevertheless, it is clear that the technology will have a substantial impact in some areas.

## Conclusions

Rapid developments in facilitating technologies such as genomics, transgenics, tissue culture, and computer systems promise dramatic increases in the scope, pace, and efficiency of wheat breeding. The most substantial effects are likely to be seen where these technologies are able to increase access to new sources of beneficial genetic variation for important agronomic traits. This, in turn, will enable the development of tools to increase the precision and cost-effectiveness of manipulating specific genes in a design-led way within wheat breeding programs. Unfortunately, the development and application of novel wheat breeding tools is constrained by insufficient public and private investment.

There is no doubt that wheat productivity would benefit from greater private sector investment. However, this will only come about in markets with strong IP protection systems or where biological protection systems (such as hybrid technologies) can be deployed. Intellectual property protection systems in many developing countries are still relatively weak and lack well established royalty collection systems. Some developing countries may muster the political will to build a strong IP protection system or negotiate a national license to retain the right to freely provide seed of new GM varieties to poor farmers. Other countries must take a careful look at hybrid technology options in order to provide a biological protection system for the private sector.

Hybrid wheat seed production is too expensive and, as a result, the price of hybrid varieties is the major constraint to greater adoption. Yet recent studies suggest that farmers' price responsiveness is high, so technologies that can provide significant cost savings through efficiency gains in seed production may have a dramatic effect on adoption (Matuschke et al. 2007). It is highly likely that viable GM solutions for low-cost wheat hybrid seed production will be available within the next 5-10 years. In this respect, hybrid rice may provide a useful model, as it appears to have suffered from similar problems (Cheng et al. 2007). However, for genetic reasons, the yield advantage of hybrids over inbred varieties may not be as high for wheat. Thus, other added-value traits may have to be the main selling point to entice farmers to adopt new hybrid varieties. Clearly, GM technologies offer diverse opportunities in this respect. Public investment in the development of transgenic technologies for hybrid seed production will likely be required to launch the process. Once transgenic cms systems have been developed, they should foster increased private sector investment in wheat research and breeding that would substantially benefit small-scale farmers in resource-poor production systems.

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# Climate Change: What Future for Wheat?

**D.P. Hodson and J.W. White**

## Introduction

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 concentrations." 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 is the most widespread cereal in terms of area planted. Bread and durum wheats (*Triticum aestivum* and *Triticum durum*) occupy an estimated 200 million ha globally (see Aquino et al., this volume). Given its importance, understanding the likely responses of wheat production to global change is strategic for anyone concerned with global food security.

Climate change encompasses many aspects, of which the foremost for wheat systems are increased warming and atmospheric $CO_2$ concentration, but associated with warming, climatologists also predict major alterations in precipitation patterns. These elements, coupled with the physiological and agronomic aspects of wheat production, are the focus of this review. The effects of climate change will differ depending on region and production environment, so we use the mega-environment (ME) concept developed by CIMMYT (Figure 1; Rajaram et al. 1994) as a framework for many of the discussions. CIMMYT wheat MEs represent global regions—not always geographically contiguous—with similar adaptation patterns based on production factors, consumer preferences, and wheat growth habits. Current ME definitions are based on quantitative agroclimatic criteria, principally temperature and water regime (Hodson and White 2007).

## Global Warming and Wheat Yields

The latest IPCC report (2007) details a linear warming trend over the last 50 years of 0.13 °C per decade, which is nearly twice the rate over the last 100 years. The total increase during the 20th century (1906-2005) is estimated at 0.74 °C. Observed temperatures in 11 of the last 12 years (1995-2006) rank this period among the 12 warmest years since instrumental records began in 1850. Warming trends have been recorded across all continents, and climate models are permitting increased confidence in near-term climate predictions. Uncertainty for longer periods reflects, in large part, uncertainty over trends in greenhouse gas emissions. Under contrasting IPCC scenarios (see IPCC 2000), the best estimates of average temperature increases by the end of the 21st century range from 1.8 °C to 4 °C.

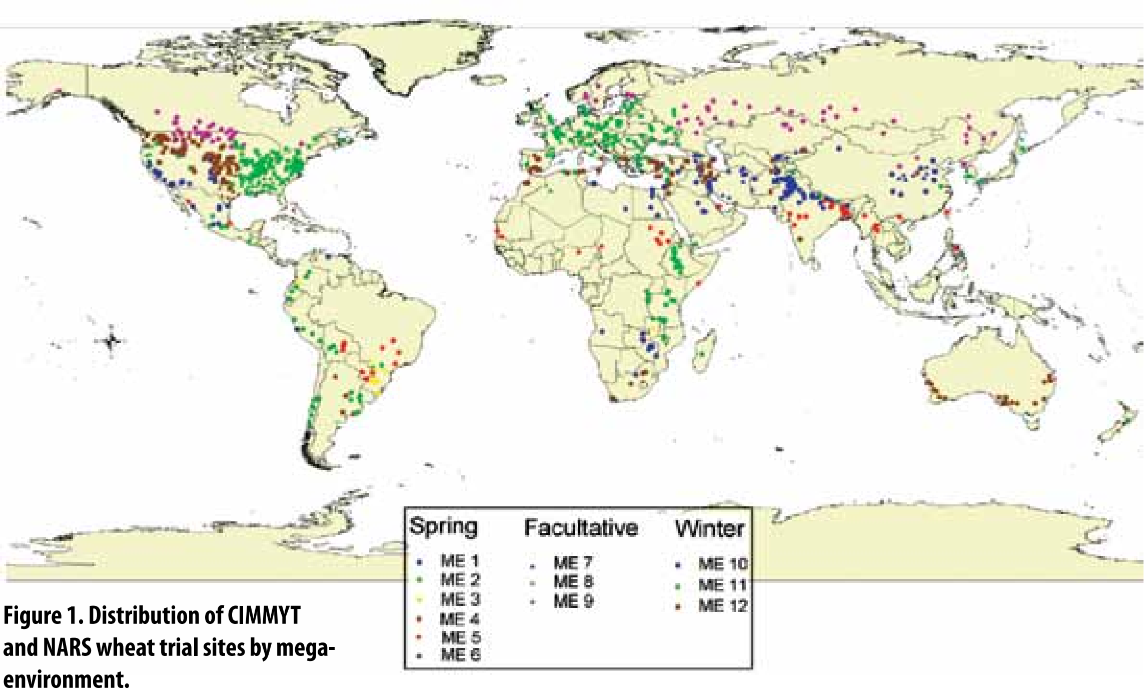

**Figure 1. Distribution of CIMMYT and NARS wheat trial sites by mega-environment.**
Source: Trethowan et al. 2005a.

Wheat is sensitive to temperature increases, but effects depend on background ambient temperature, stage of crop development, and variety. 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 stages are especially detrimental: temperatures above 30 °C at anthesis can damage pollen formation and reduce yield.

## Elevated Atmospheric $CO_2$ and Wheat Yields

Carbon dioxide is the most important greenhouse gas. Levels have increased from around 280 ppm in the pre-industrial era to around 380 ppm in 2005. These levels greatly exceed natural ranges during the past 650,000 years, and use of fossil fuels is the primary source of elevated levels of $CO_2$ (IPCC 2007). Apart from positive radiative forcing and surface warming, increasing $CO_2$ concentrations have the potential to increase plant growth and yield, primarily through increased photosynthesis, with benefits being greater for $C_3$ crops such as wheat (Kimball 1983). A review of 50 studies on the effects of elevated $CO_2$ on wheat yields (Amthor 2001) concluded that increasing $CO_2$ per se will normally be positive, but benefits will vary with the availability of water and nutrients, and temperature. Whether such benefits will offset the negative effects of warming is therefore a critical issue when assessing wheat production under global climate change.

Experimental determination of crop response to $CO_2$ fertilization is more difficult than might be expected. Meta-analyses across studies typically show wheat yield increases from 10 to 20% at 550 ppm $CO_2$, depending on nitrogen and water management (Kimball et al. 2002), although there is active debate on the magnitude of these values (compare Long et al. 2006 and Tubiello et al. 2007). Production increments of this order of magnitude were the basis for many of the climate and crop modeling studies reviewed by the IPCC (IPCC

TAR 2001), resulting in the suggestion that offsets from $CO_2$ fertilization would result in a net gain in crop production.

Soil fertility, water availability, and temperature can alter responses to $CO_2$. Kimball et al. (2001) report wheat yield increases of only 9% under low N conditions and elevated $CO_2$, versus a 16% increase at high N. With water deficit, yield increases attributed to $CO_2$ are larger relative to near-optimal management—e.g., the 23% increase reported under a 50% irrigation scheme in the Kimball et al. study. This interaction results from the partial closure of stomata under elevated $CO_2$, which reduces transpiration and improves water use efficiency. However, Kimball and Bernacchi (2006) estimated that the water use benefit would be completely offset by the direct effects of a 3.5 °C increase on transpiration rate. There is also evidence that elevated $CO_2$ levels under low N conditions act synergistically to exacerbate the detrimental effects of low N on grain quality (Kimball et al. 2001).

## Climate Change across Wheat Mega-environments

Key elements of global climate change––namely, warming and elevated $CO_2$ concentrations—and some of their biological effects on wheat have been outlined in the previous sections. We will review the implications of these changes for future wheat production on a global and regional basis within the framework of the CIMMYT MEs (see Table 1). 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.

Assessments of yield responses are derived mainly from applications of crop growth simulation models coupled with global or regional climate change models and run under a range of emission scenarios. It must be recognized that there are limitations and uncertainties associated with both types of models and, often, variable results, depending on the assumptions and parameters used. Typically, work has focused on a suite of 5 to 10 widely-accepted advanced Global Circulation Models (GCMs)—e.g., Hadley center (HadCm3) or CSIRO-MK3—coupled with mainstream crop simulation models such as CERES and APSIM, and evaluated under the standard range of IPCC SRES. Despite variation, there is an emerging consensus relating to productivity trends, particularly at the aggregate global level.

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 to 3 °C) occur. However, further warming, even in temperate regions, causes yields to decrease. In subtropical and tropical regions, wheat is often already near its limit of maximum temperature tolerance, so small temperature increases (1-2 °C) reduce yield. 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).

Translated into impact on specific mega-environments, the greatest concerns appear to be for mega-environments 1 to 5, which include subtropical to tropical spring wheat regions (Table 1). An estimated 9 million ha of wheat in these regions experience yield losses due to heat (Lillemo et al. 2005). Heat-stressed environments are classified as ME5, with subdivisions for predominantly humid or dry

**Table 1. Suggested impacts of global warming and increased $CO_2$ on wheat production in different mega-environments (MEs). A net positive impact of $CO_2$ on productivity should occur across all MEs. P = positive impact, N = negative, and U= uncertain.**

| Mega-environment | Representative sites | Global change concerns/opportunities |
|---|---|---|
| **Spring wheat** | | |
| ME1: Favorable, irrigated, low rainfall<br>Estimated wheat area: 36 M ha | Gangetic Valley, India<br>Indus Valley, Pakistan<br>Nile Valley, Egypt<br>Yaqui Valley, Mexico | N–Rising temperatures result in large areas evolving to ME5<br>N–Reduced precipitation in subtropical regions restricts irrigation<br>P–Reduced irrigation due to impact of elevated $CO_2$ on water use efficiency |
| ME2A: Highland, summer rain<br>Estimated area: 5 M ha | Kulumsa, Ethiopia<br>Toluca, Mexico | N–Rising temperatures result in large areas evolving to ME5<br>N–Reduced precipitation result in areas evolving to ME4 |
| ME2B: Lowland, winter rain<br>Estimated area: 3 M ha | Izmir, Turkey<br>Pergamino, Argentina | N–Rising temperatures result in large areas evolving to ME5<br>U–Changes in precipitation patterns in areas will have variable effects |
| ME3: High rainfall, acid soil<br>Estimated area: 2 M ha | Passo Fundo, Brazil<br>Mpika, Zambia | N–Rising temperatures result in large areas evolving to ME5<br>U–Changes in precipitation patterns in areas will have variable effects |
| ME4: Low rainfall<br>Estimated area: 14 M ha | (See representative sites for ME4 sub-environments below) | N–Rising temperatures exacerbates water deficits, either further reducing yields or making production uneconomical<br>P–Reduced water deficits through impact of elevated $CO_2$ on water use efficiency |
| ME4A: Winter rain or Mediterranean-type climate<br>Estimated area: 8 M ha | Aleppo, Syria<br>Settat, Morocco | N–Rising temperatures result in large areas evolving to ME5<br>N–Changes in precipitation patterns likely to increase drought risk |
| ME4B: Winter drought or Southern Cone-type rainfall<br>Estimated area: 3 M ha | Marcos Juarez, Argentina | N–Rising temperatures result in large areas evolving to ME5<br>N–Changes in precipitation patterns likely to increase drought risk |
| ME4C: Stored moisture<br>Estimated area: 3 M ha | Dharwar, India. | N–Rising temperatures result in large areas evolving to ME5<br>U–Changes in precipitation patterns in areas will have variable effects |
| ME5: Warm: humid/dry<br>Estimated area: 9 M ha | Joydebpur, Bangladesh<br>Chiangmai, Thailand<br>Encarnacion, Paraguay<br>Kano, Nigeria<br>Wad Medani, Sudan | N–Rising temperatures result in large areas becoming unsuitable for wheat<br>N–Increasing biotic stress<br>U–Elevated $CO_2$ may increase water use efficiency, but the same mechanism implies increased canopy temperature, which likely would exacerbate heat stress |
| ME6: High latitude (> 45°N or S)<br>Estimated area: 45 M ha | Urumqi, Xinjiang, China<br>Astana, Kazakhstan<br>Harbin, Heilongjiang, China | P–Rising temperatures lengthen growing season and permit marginal areas to become productive<br>P–Reduced risk of winter-kill allows conversion to more productive winter wheat |
| **Facultative wheat** | | |
| ME7: Favorable, moderate cold, irrigated | Zhenzhou, Henan, China | U–Reduced cold stress allows growing spring wheat, possibly reducing yield potential but shortening growing season<br>P–Reduced irrigation due to impact of elevated $CO_2$ on water use efficiency |
| ME8: High rainfall (> 500 mm), moderate cold | Temuco, Chile<br>Corvallis, Oregon | U–Reduced cold stress allows growing spring wheat, possibly reducing yield potential but shortening growing season<br>U–Increasing biotic stress |
| ME9: Semi-arid, moderate growing rainfall | Diyarbakir, Turkey<br>Vernon, Texas | U–Reduced cold stress allows growing spring wheat, possibly reducing yield potential but shortening season<br>U–Changes in precipitation patterns in areas will have variable effects<br>P–Reduced water deficits through impact of elevated $CO_2$ on water use efficiency |
| **Winter wheat** | | |
| ME10: Favorable, cold, irrigated | Beijing, China | P–Warmer winters reduce severity of winter-kill, increasing yields<br>N–Warmer spring and summer hasten grain-filling<br>P–Reduced irrigation due to impact of elevated $CO_2$ on water use efficiency |
| ME11: High rainfall, cold | Odessa, Ukraine<br>Krasnodar, Russia | P–Warmer winters reduce severity of winter-kill |
| ME12: Semi-arid, low rainfall, cold | Ankara, Turkey<br>Manhattan, Kansas | P–Warmer winters reduce severity of winter-kill<br>P–Reduced water deficits through impact of elevated $CO_2$ on water use efficiency<br>N–increased insect problems |

conditions. Wheat regions already at the limit for heat tolerance are most likely to suffer and may see substantial area reductions. Similarly, under warming, large areas of ME1 will transition to ME5, as illustrated in Figure 2 for South Asia. Positive impacts for ME1, however, are anticipated from $CO_2$-driven increases in productivity, accompanied by increased water use efficiency.

High elevation, high rainfall environments (ME2A) will experience reductions in area as the elevation band providing suitable temperatures for wheat is displaced upwards. An agroclimatic study on Ethiopia (White et al. 2001) revealed that the current wheat area is largely delimited by high temperature and that warming would greatly reduce the area suitable for wheat.

Since drought and warmer temperatures are often associated, global warming may result in low rainfall ME4 areas becoming unsuitable for wheat due to the combined effects of warming and water deficits. This trend may be partially offset by $CO_2$-driven increases in productivity and water use efficiency.

In contrast to negative to neutral projections, cooler, high-latitude spring wheat environments (ME6) should benefit in multiple ways from climate change. Warmer temperatures should allow earlier sowing and reduce chances of late-season frost. Some areas may convert to more productive winter wheats (MEs 10 to 12) as risk of winter-kill declines. Furthermore, areas previously too cold for spring wheats, often used to produce rye or barley, may become suitable for spring wheat. Throughout the region, beneficial effects of $CO_2$ on productivity and water use efficiency should also be observed.

Regions for facultative wheats (MEs 7 to 9), which are intermediate to spring and winter wheats, should become more suitable for fall-to-winter-sown spring wheats as risk of cold damage decreases. The effect on spring wheat yield potential in these environments is more uncertain. Alternately, warmer winters may increase options for growing less cold-tolerant crops.

As discussed under ME6, warmer winters will allow conversion of spring wheat regions to winter wheats, but the fate of current warmer winter wheat areas (e.g., of Texas and Oklahoma in the US) is less clear. Heat stress during grain-filling may limit yield, but elevated $CO_2$ should increase overall productivity and reduce water deficits.

More detailed regional studies are increasingly being undertaken, linking downscaled global change scenarios with predictions from

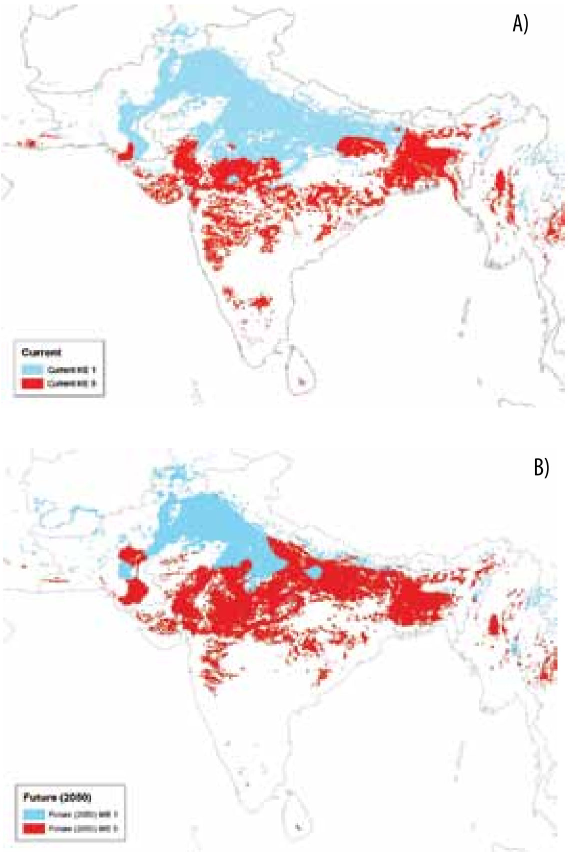

**Figure 2. Principal wheat mega-environment zones in South Asia. ME1: high potential, favorable, irrigated (blue); ME5: heat-stressed, lower potential (red); under a) current climatic conditions, and b) a future climatic scenario.**

Source: Adapted from Hodson and White (2007).

process-based models of crop growth and development; e.g., in India and China (DEFRA 2005). In India, simulations predict marked increases in both rainfall and temperature (up to 3 to 4 °C) in the next 100 years. Wheat yields are predicted to decrease in most areas, with decreases of 1.5 to 5.8% in subtropical areas but larger reductions in lower-potential and warmer tropical areas. In China, similar temperature increases are predicted, but implications for wheat are uncertain depending on the nature of $CO_2$ fertilization effects. Excluding the $CO_2$ effect, models predicted up to 20% yield decreases under worst-case emission scenarios, but with high spatial variability. Conversely, inclusion of the $CO_2$ response resulted in yield increases over most of China. For irrigated wheat to respond to $CO_2$, however, adequate water and nutrients would be needed. Impacts were more adverse for spring wheat than winter wheat.

## Other factors

Other aspects of global climate change are likely to have direct or indirect effects on future wheat production. Two important aspects are changes in precipitation means and variability, and changes in biotic stress patterns. All three types of changes will undoubtedly be important for future wheat production, but considerable uncertainty exists in estimating their effects, and only brief consideration is given here. Climate models often predict substantial changes in tropical rainfall, but drawing out expected changes is difficult, as there is little agreement between different models and high spatial variability. In a recent, multi-model study of tropical rainfall (Neelin et al. 2006), trends included drying trends in specific regions, most notably the Caribbean/Central American region (very strong model agreement), and precipitation increases, notably in the Southeast Asian monsoon and equatorial Pacific regions. Increasing amplitude in drying trends was predicted with warming. In terms of extreme events (heavy precipitation events or intense drought), the evidence suggests that these are increasing and will continue to do so (IPCC 2007). Several studies point to a more volatile, uncertain world in which risk of annual crop failure in certain regions is likely to increase (e.g., Parry et al. 2004).

This increase in climate variability has major implications for a breeding program, since breeding for site-specific adaptation becomes less feasible. For example, in Tunisia major wheat growing areas were classified in one year as ME4A (terminal drought) and in the following as high rainfall (ME2). CIMMYT's wheat breeding program has always emphasized the development of wheat cultivars with stable yields over a wide range of environments. Such cultivars, identified through testing in the International Wheat Improvement Network, form the genetic basis to further enhance tolerance to heat and drought stress.

Insects, diseases, and weeds will undoubtedly respond to global change; however, as a result of the complex dynamics between hosts and pests, and the large variation in pest response to climatic conditions and $CO_2$ levels, trends are difficult to predict and beyond the scope of this review. In broad terms, warmer, more humid conditions usually favor insect pests and diseases. However, perhaps equally important are specific, localized climatic effects during critical crop stages. The re-emergence of fusarium head blight in the US and Canada may in part be a response to the warming trend observed in recent years. In the Indo-Gangetic Plains of South Asia, spot blotch is increasing in severity, a change that is associated with increasing night-time temperatures in March (Sharma et al. 2007). Similarly, in regions where sowing dates of winter wheat are delayed until frosts have reduced levels of pests such as Hessian fly and aphids, warming may force later sowings.

## Wheat quality

Further to the analysis provided by Meng et al. (this volume), climate change will undoubtedly affect wheat quality, and this deserves comment. Warming will result in a reduced grain-filling period, which is 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). However, interactions with soil moisture, nitrogen, and temperature are expected. Negative effects of elevated $CO_2$ are mitigated by either reduced moisture availability and/or increased temperature, but elevated $CO_2$ may enhance the detrimental effects of low nitrogen on wheat quality (Kimball et al. 2001). Since elevated $CO_2$ enhances water use efficiency, regions that use mild water deficits to enhance grain quality may be adversely affected. On balance, elevated $CO_2$ will likely lower wheat quality, especially in systems where nitrogen is already limiting.

## Adaptation to climate change through wheat improvement

The argument is often made that given the slow rate of environmental change, crop improvement could provide the required adaptation to warmer conditions and elevated $CO_2$. In areas where temperatures and moisture are non-limiting, this indeed seems likely. However, given that selecting for heat stress tolerance in wheat has long challenged wheat breeders, optimism over solving problems related to global warming merits review. Similarly, limited studies on genetic differences in wheat's responsiveness to $CO_2$ variation are far from conclusive.

Crosses with landraces originating from heat and drought stressed locations express adaptation to abiotic stress, including heat tolerance. Conceptual models have been developed for stress tolerance (see Reynolds and Borlaug 2006) and used to select complementary parents based on physiological traits. Reduced canopy temperature is associated with heat tolerance and now used as an early-generation selection tool (Reynolds et al. 1998).

Re-matching wheat phenology to cropping seasons also has potential to offset the impacts of warming. Since warming increases rates of development, which results in earlier flowering and maturity, selection for compensatory lateness may reduce the expected yield decline. However, in areas already experiencing heat stress, temperatures at the end of the cropping cycle are so high that grain is affected, and current efforts are geared towards finding earlier lines (e.g., in Pakistan). Cultivar differences in wheat phenology are largely determined through the combined effects of vernalization requirement, photoperiod response, and earliness per se; all three traits are well understood genetically (van Beem et al. 2005; White 2006). We note that most simulation studies that assess the impacts of global warming ignore the potential benefits of re-matching phenology.

Evidence for genetic differences in response to elevated $CO_2$ suggests two main mechanisms: responsiveness of photosynthesis to elevated $CO_2$ and ability of the crop to utilize additional assimilate. Comparing six winter wheats representing a historic series, Manderscheide and Weigel (1997) found no genotype x $CO_2$ effect for various leaf traits, although other studies indicate that genetic differences in photosynthetic response to $CO_2$ may exist. Cultivar comparisons by Manderscheide and Weigel (1997) and Ziska et al. (2004) under elevated $CO_2$ both emphasized the importance of changes in partitioning and yield components, suggesting that in order for plants to fully benefit from elevated $CO_2$, sink strength should be increased. Given the large variation in tillering ability and yield components in current wheats, as well as historic success in modifying the harvest index, it seems likely that sink strength can be adjusted through routine yield improvement breeding. Counterbalancing this optimism, however, is the caution that any selection for improved responsiveness to elevated $CO_2$ will likely reduce the benefits through increased water use efficiency.

The potential for wheat improvement to exploit or compensate for the effects of global climate change should also be judged in the light of expected progress in breeding for abiotic stress tolerance. The genetic base of wheat is being broadened by the use of so-called "synthetic wheats" to introduce a new spectrum of genes from wild wheat progenitors. This approach is providing important advances for tolerance to abiotic stresses, including drought, salinity, and heat (Trethowan et al. 2005b; Crouch et al., this volume). Recent advances in gene discovery, plus detection and analysis of markers, suggest that molecular biology will play an increasing role in breeding for complex traits such as drought and heat tolerance in the coming decades (Crouch et al., this volume).

Taken in balance, heat stress tolerance remains a serious challenge, although there is reason for optimism. Re-matching phenology to cropping seasons seems highly feasible and merits greater attention. There appears to be good potential for breeding wheats that are more responsive to elevated $CO_2$ but at the expense of reducing benefits of elevated $CO_2$ on water use efficiency.

## Adaptation to climate change through crop management

Shifting sowing dates is the most obvious mechanism to adapt to warming, although it may be a limited option in some spring wheat areas with short cropping seasons. At higher latitudes, earlier spring sowing under warming conditions should allow for a longer growth cycle, as well as offer potential for harvesting crops before summer heat stress becomes limiting. In irrigated tropical areas, where wheat is often one component of a complex cropping system, wheat sowing date depends on the previous crop. The rice-wheat cropping system of South Asia provides a good example (see Erenstein, this volume). Wheat sowing is delayed until after rice, the main cash crop, is harvested, and large portions of the wheat areas are currently planted late, which increases the risk of detrimental, yield-reducing, pre-monsoon heat stress. Under warming scenarios for this region, early sowing of wheat to escape terminal heat stress will become ever more critical. Conservation agriculture, particularly direct seeding of wheat after rice, can reduce or eliminate land preparation after rice and save up to 30 days, thus facilitating early sowing of wheat and reducing or avoiding climate change-induced heat stress (see Sayre and Govaerts, this volume). In such reduced tillage or no-till systems, decreasing diesel consumption and greenhouse gas production would be additional benefits in terms of climate change mitigation.

Expanded adoption of improved management practices clearly can help ensure the future viability of wheat production in certain areas. However, in some regions even the combined effect of improved varieties and improved management may prove insufficient to combat heat-stress, and the best option for growers may be to replace wheat with better adapted crops.

## Implications for research

Climate change will have a major impact on wheat production. Increasing temperatures, elevated levels of $CO_2$, variability in precipitation, and changes in pests and diseases will all play a role. At the global level, under modest warming scenarios, the overall balance for grain production is likely to be positive. In specific regions, gains will likely come from $CO_2$ fertilization effects, favorable growing conditions, switches from spring to winter wheat, and potentially expanded areas. Cool temperate wheat regions, especially in the northern hemisphere, are likely to be beneficiaries, assuming that changes in disease, pest, and weed pressures prove manageable. However, these potential aggregate gains mask serious detrimental impacts, particularly for wheat producers in subtropical to tropical regions. These areas are likely to suffer primarily due to increasing abiotic stress, especially heat, and changing biotic stress patterns.

Area reduction or crop substitution will likely occur in regions already at the limit of adaptation. In systems where N is already limiting, elevated $CO_2$ levels may have a detrimental effect on wheat quality. Crop improvement and improved crop management will be vital to counteract the negative aspects of climate change and allow efficient exploitation of the potential benefits of elevated $CO_2$. This panorama presents major challenges that CIMMYT and its global wheat partners must deal with successfully, if the threat of climate change in the developing world is to be countered.

The implications for wheat research include a higher priority for breeding for heat stress, water use efficiency, and elevated $CO_2$ levels, as well as re-matching phenology to cropping seasons. Development of improved cropping system management systems that facilitate timely sowing (to reduce subsequent heat stress) and increase water use efficiency will play an important role.

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# Conservation Agriculture for Sustainable Wheat Production

**K.D. Sayre and B. Govaerts**

## Introduction

> ***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.***
>
> Anonymous

This down-to-earth statement illustrates the paramount importance of farmers—small-scale and large, in both developing and developed countries—employing appropriate crop management technologies that will not only generate cost-effective, stable, crop production opportunities and allow varieties to yield well, but will also conserve the integrity and sustainability of the soil resource base while ensuring the efficient use of scarce water resources. The multitude of the world's farmers, as well as three billion urban consumers, must rely on sustainable food production systems, including wheat production, for their livelihoods.

Current wheat management systems are threatened by increasing competition for ever-scarcer water resources, combined with the continued use by most farmers of highly inefficient irrigation systems. Despite the availability of improved wheat varieties with increased yield potential, the potential increase in wheat production is often not attained because of poor crop system management. There are increasing concerns that global agricultural activities, including those associated with wheat production, make significant contributions to greenhouse gas (GHG) emissions associated with climate change. Extensive tillage can lead, in turn, to the rapid breakdown of soil organic matter and the associated release of $CO_2$ into the atmosphere, especially when combined with in situ burning of crop residues (Reicosky 2001). Tillage also entails the extensive burning of fossil fuels that contribute to GHGs and climate change. Wherever these practices have been persistently used over time, soil erosion losses have magnified and the soil resource base has been steadily degraded (Montgomery 2007). Many soils have been worn down to their nadir for most soil parameters essential for effective, stable, and sustainable crop production, including soil physical factors (structure/aggregation, which enhances water use efficiency by fomenting improved water infiltration into the soil), soil chemical factors (especially soil organic matter, salinity, sodicity, and nutrient balance), and soil biological diversity factors (marked reductions for most positive biological soil entities combined with the likely facilitation of soil-borne pathological organisms).

Soil degradation in all its nefarious forms is not a prelude to mass starvation, as analysts once feared. Nevertheless, it is eroding crop yields and contributing to malnourishment in many corners of the globe (Science, 11 June 2004, p 1617). Cases from Africa showed that nutrient depletion will initially support declining yields, and will later result in low yields at low fertility levels. In the latter case, food security is generally at stake (Smaling and Dixon 2006). In addition, the continuing inefficient management of increasing levels of nitrogen fertilizers used by many wheat farmers can raise production costs while releasing NO and $NO_2$ to the atmosphere;

these GHGs are even more deleterious than $CO_2$ and are also responsible for the widespread leaching of high levels of nitrate pollution into underground water tables. A direct consequence of farmers' persistent use of traditional agronomic practices is rapidly increasing production costs associated with the inefficient use of inputs, whose costs continue to rise. In addition, any new, more sustainable wheat management strategies must be compatible with crop diversification policies that may evolve to meet new consumer or industrial requirements. All these issues must be addressed within a scenario of decreasing area available for crop production because of urbanization, industrial expansion, and land used to produce biofuel instead of food.

Despite the large number of improved wheat varieties released each year; global yield growth has slowed down (see the Overview, this volume). Furthermore, the results from CIMMYT's long-term, genetic yield potential trials have demonstrated this for high-yield, irrigated production conditions (Sayre et al. 2006). If farmers do not adopt sustainable systems developed by agronomists, breeders will need to invest more and more resources in improving traits to "fix" problems related to soil fertility that is declining as a consequence of poor crop and resource management; these financial resources would then not be available to improve grain yield, quality, or stress tolerance. CIMMYT's long-term conservation agriculture trials have clearly indicated that improved wheat germplasm does not achieve its genetic yield potential without good cropping systems management: the same wheat variety with similar input use but different planting/tillage method results in yield differences of up to 35% (Govaerts et al. 2005). Therefore, sustainable wheat management will not be obtained with improved crop varieties alone. In fact, it is the understanding of genotype x system interactions that is crucial to the integration of crop improvement and crop management.

## Toward Sustainable Wheat Systems Management

In recent years, farmers who have been concerned about the lack of sustainability of their crop production and farming systems and ever-increasing production costs have begun to adopt and adapt improved systems management practices that lead to the ultimate vision of sustainable conservation agriculture (CA) solutions. The term conservation agriculture has been used over the last seven or eight years to distinguish this more sustainable system from the narrowly defined "conservation tillage," by de-emphasizing the tillage and focusing on a more integrated approach to improve the sustainability of differing cropping systems. Conservation agriculture involves major changes in various aspects of farm operations that render them very different from widely used, traditional, tillage-based farming practices. Conservation agriculture is characterized by the appropriate application of the following basic tenets to contrasting cropping systems:

- Dramatic reductions in tillage.
  Ultimate goal: Zero-till or controlled-till seeding of all crops in a cropping system.
- Retention of adequate levels of crop residues on the soil surface.
  Ultimate goal: Retention of sufficient residue on the soil surface to protect the soil from water run-off and erosion, improve water productivity, and enhance long-term sustainability.
- Use of sensible crop rotations.
  Ultimate goal: Employ economically viable, diversified crop rotations to help moderate possible weed, disease, and pest problems.
- Perception by farmers of the potential for very near-term, improved economic benefits and livelihoods.
  Ultimate goal: Secure and value farm assets.

These principles define a generic approach to crop and soil management that is not location-specific; i.e., the knowledge, the approach, and fundamental and strategic principles are international public goods. Obviously, specific and compatible management components (weed control tactics and herbicide applications, nutrient management strategies, appropriately-scaled implements, etc.) will need to be developed through adaptive research to facilitate farmer adoption of CA under contrasting agroclimatic conditions or production systems, much as specific crop cultivar traits (grain color, end-use quality characteristics, genetic disease resistance requirements, etc.) have been developed for specific production situations and environments. In reality, as more CA-oriented, resource-conserving technologies are incorporated, a farming system progressively approaches a full, sustainable CA system.

Farmer acceptance of all the basic tenets of CA may not happen immediately, but rather in a step-wise manner that reduces tillage and allows retention of more crop residues than currently practiced. The success of step-wise CA adoption will vary in differing cropping systems, and there may be some, particularly rainfed cropping systems, where initial full adoption may be necessary to achieve major sustainable improvements.

Successful farmer adoption of the first three CA tenets will mean altering generations of traditional farming practices and implements (including hoes), especially those applied by many small- and medium-scale farmers in developing countries who may have had minimal exposure to new farming technologies. In fact, changing the mind-set, not only of farmers but also of scientists, extension agents, private sector members, and policy makers, is a major challenge associated with the development, transfer, and farmer adoption of appropriate CA technologies. As such, the movement towards CA comprises a sequence of systems management improvements where the principles of reduced/conservation tillage are applied in combination with appropriate crop rotations and rational amounts of crop residue retention to achieve an integrated sustainable production system. Obviously, the final CA tenet listed above (improved economic benefits and livelihoods) is not unique to CA, but is a common aim associated with the adoption of all new farming innovations that must guide the evolution of suitable CA technologies. Farmers may recognize there are serious sustainability issues on their farms, but for CA to be a rational solution, its adoption must be driven by economic advantage; otherwise, these detrimental issues will likely not be adequately resolved.

There are farmers in regions of Brazil, Paraguay, Argentina, Australia, and India who have successfully adopted CA principles; some of them represent the most cost-effective wheat producers worldwide.

## Reasons to Invest in Conservation Agriculture

Conservation agriculture benefits both the global society as well as individual farmers. Some of its benefits accrue almost immediately, while others develop over time, as the dynamics for the onset of benefits may vary for different agro-climatic/production systems (Sayre 1998; Derpsch 1999). These benefits include the following effects (adapted from Bradford and Peterson, 2000).

### Short-term effects

- Reduced production costs; savings in fuel and labor costs related to reductions in the use of tractors, associated tillage implements, and labor requirements for land preparation.
- Reduced turn-around time between crops to improve timeliness (harvest today, plant tomorrow) when conditions allow immediate sequence cropping.
- Marked improvements in water use efficiency and productivity, especially in rainfed conditions, due to increased water infiltration, which reduces run-off, and to less evaporation of soil moisture through the retention of adequate levels of crop residues on the soil surface.
- Reduced soil erosion from decreased water run-off associated with the presence of surface-retained residues.
- Moderation of soil temperature extremes.

### Medium- to long-term effects (5-10 years)

- Increased soil organic matter resulting in better soil structure, greater cation exchange capacity and thus higher nutrient availability, and greater water-holding capacity.
- Enhanced carbon sequestration in the soil, mitigating the release of $CO_2$ as a greenhouse gas associated with climate change.
- More efficient nutrient utilization and cycling.
- Increased biological activity in both the soil and aerial environments, leading to opportunities for biological and integrated control of pests and diseases.
- Higher and more stable crop yields.
- Reduced risk.

In 1990, CIMMYT established a long-term trial in El Batan, Mexico, to investigate the long-term effects of different tillage, crop rotation, and crop residue management practices for rainfed cropping. Its purpose is to compare CA tenets with conventional tillage-based practices for wheat and maize production in the surrounding rainfed region and to provide a means to develop CA for rainfed cropping systems with similar agroclimatic conditions. Results from the trial confirm the above-mentioned benefits of CA in the rainfed highlands of Mexico (Govaerts et al. 2005; 2006a; 2006b; 2007a; 2007b). Wheat grain yield results over a 10-year period (1996 to 2005) are presented in Figure 1. Each year the cultivars most highly recommended by CIMMYT breeders have been used (and changed as needed); all weed control and fertilizer management have paralleled recommendations (modified as needed). Tillage, residue management, and rotations have remained constant in the 16 static treatments. As Figure 1 illustrates, the best CA practices provided consistently higher, more stable wheat yields. It is obvious, therefore, that if farmers in this region continue to use tillage-based practices and crop residue removal on their already degraded soils, they will not obtain the maximum yield response, nor will there be a full return on the investments used to develop new, improved cultivars. Similarly, with the current traditional wheat and maize cropping practices, other inputs (in particular, rainfall in this case) will not be efficiently utilized.

Estimates of the returns above variable costs from the long-term trial described above for rainfed wheat clearly indicate the potential economic advantage to farmers, especially small- and medium-scale farmers, if they have the means to adopt CA technologies (see Figure 2). When comparing the profile of benefits and costs associated with conservation agriculture on the farm, regional, regional/national, and global scales, there is a divergence between the social desirability of CA and its potential appeal to individual farmers. Fortunately, the net financial impact and the reduced risk at the individual farm scale are positive (Knowler and Bradshaw 2007) and, as such, a mayor driver for adoption.

## Farmers' Response: Adoption of Conservation Agriculture

Over the past 20 years, there has been an increasingly rapid adoption and support to promote farmer adoption of CA, driven mainly by dramatic tillage reductions. There was a rather slow pace of development and adoption of CA technologies over the previous

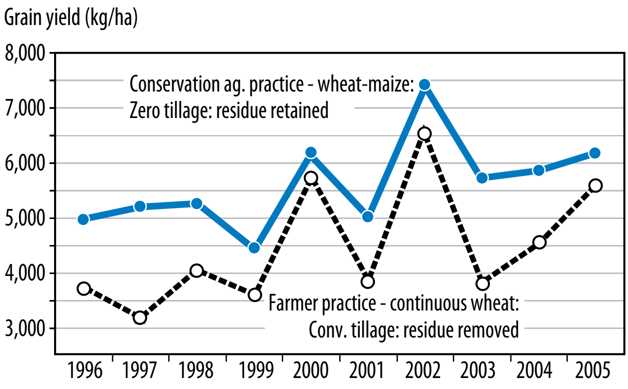

**Figure 1. Comparison of rainfed wheat yields for the most common farmer practice versus the best conservation agriculture practices, El Batán, Mexico, 1996-2005.**

20 years, as pioneering farmers confronted and resolved new management issues associated mainly with efforts to achieve marked tillage reductions (especially zero-till seeding), while simultaneously seeding into and managing surface-retained crop residues. One success story for farmer adoption of CA occurred in Brazil during the last 30 years. Adoption can be characterized by a lag phase that may last 10 to 20 years but which is followed by rapid expansion as the necessary ingredients for success are put in place.

Derpsch (2005) has estimated, based on information from various sources, that there are approximately 96.5 million hectares worldwide of crops grown using zero-till-based CA technologies (see Table 1). Statistics on the area under cultural practices that can be considered CA are difficult to obtain, and it is likely that such figures, when available, mask very different system practices, some of which might not explicitly adhere to the underlying CA tenets, but rather are in the process of becoming CA. Of the estimated 96.5 million hectares worldwide under CA, about 92% is located in five countries: USA (26% of the total area), Brazil (24%), Argentina (19%), Canada (13%), and Australia (9%). Four of these five countries (not Brazil) are the leading adopters of zero-till seeding, the major wheat exporters outside the EU, and most likely the most economically efficient wheat producers. Apart from a few exceptions, current adoption of CA involves relatively large commercial farms, and the use of heavy tractors and large-scale equipment (especially seeders). More than 96% of the total area under CA comprises rainfed production systems involving mainly wheat (at least 50% of the world total area under CA is devoted to wheat production), maize, and soybean, although there are substantial areas planted to canola, sorghum, sunflower, and grain legumes in several countries. Current levels of CA adoption in developing countries are low (and poorly documented) and involve farmers in North Africa, west and central and South Asia, and China (although China is now devoting considerable resources to develop CA for both rainfed and irrigated production systems). Most European countries (especially in northern Europe) are in the early stages of farmer adoption of CA.

Except for the areas mentioned above, there has been limited CA adoption in developing countries. Use of CA under irrigated conditions, especially gravity-based irrigation water-delivery systems, is negligible, and small farmers in general (see exceptions given below) seem to be left out. However, the latter is not because of CA as such, as has been proven by some well-documented examples. On small farms in Brazil there are an estimated 200,000 ha where permanent CA is being practiced, especially in the States of Parana, Santa Catarina, and Rio Grande do Sul; there is also a considerable area in Paraguay

**Table 1. General overview of conservation agriculture/no-tillage adoption ('000 hectares), 2007-08.**

| Country | Area |
|---|---|
| USA[1] | 26,593 |
| Brazil[2] | 25,502 |
| Argentina[3] | 19,719 |
| Canada[4] | 13,481 |
| Australia[5] | 12,000 |
| Paraguay[6] | 2,400 |
| China[7] | 1,330 |
| Kazakhstan[8] | 1,200 |
| Bolivia[9] | 706 |
| Uruguay[10] | 672 |
| Spain[11] | 650 |
| South Africa[12] | 368 |
| Venezuela[13] | 300 |
| France[14] | 200 |
| Finland[15] | 200 |
| Chile[16] | 180 |
| New Zealand[17] | 162 |
| Colombia[18] | 100 |
| Ukraine[19] | 100 |
| Russia[20] | ? |
| Others (Estimate) | 1,000 |
| **Total** | **105,863** |

*Source:* Derpsch, R. and Friedrich, T., 2008, unpublished data. Information provided by: 1) CTIC, 2007; 2) FEBRAPDP, 2005/06; 3) AAPRESID, 2006; 4) Dr. Doug McKell, Soil Conserv. Council of Canada, 2006; 5) Bill Crabtree, 2008, 6) MAG & CAPECO, 2008; 7) Li Hongwen, 2008; 8) Mekhlis Suleimenov, 2007 ;9) ANAPO, Bolivia, 2007, 10) Miguel Carballal AUSID, 2007; 11) Emilio González-Sánchez, AEAC/SV, 2008; 12) Richard Fowler, 2008; 13) Rafael E. Perez, 2004; 14) APAD, 2008; 15) Timo Rouhianinen, FINCA, 2008; 16) Carlos Crovetto, 2008; 17) John Baker, 2008; 18) Fabio Leiva, 2008; 19) Estimate by the authors

(Derpsch 2005). In Ghana, by 2002 there were over 100,000 small farmers producing maize using CA, and pockets of adoption on small farms have been reported in several other countries (Ekboir 2002). The lack of financial resources can be a major constraint to small farmers faced with the initial investment to modify existing sowing equipment for the adoption of CA. Often the lack of research on crop management practices for CA systems is a major impediment to the spread of CA. In other cases, the free grazing of livestock on crop stubble reduces the retention of residues and soil cover.

Therefore, over the past 15 years, CIMMYT agronomists have been cooperating with national agriculture research institutions (NARSs) in several developing countries to help catalyze CA technology development and farmer adoption. These countries include Bolivia, where CA is being adopted at a rapid pace, particularly in the rainfed wheat, soybean, and maize production systems in the eastern lowlands bordering Brazil. Similar collaborative activities in northern Kazakhstan have resulted in the development of appropriate CA seeders and technologies with the potential to both intensify and diversify the mainly mono-crop wheat rotation in rainfed wheat-fallow systems (Patrick Wall, CIMMYT rainfed CA agronomist, pers. comm.). But again, nearly all these efforts involve rainfed production systems.

The wheat crop provides an excellent example to illustrate the difference in agroecology of a given crop when comparing developed versus developing countries. More than 95% of wheat produced in developed countries comes from rainfed production systems, and less than 5% is produced under irrigation. In contrast, in developing countries nearly 60% of all wheat is produced under irrigation—chiefly in South Asia (India, Pakistan, Bangladesh, and Nepal), West Asia (Iran and Afghanistan), Central Asia (Uzbekistan, Turkmenistan, Kyrgyzstan, Tajikistan, and southern Kazakhstan), North Africa (Egypt and Sudan), China, and Mexico. Given the importance of irrigated wheat in many developing countries and the lack of available, suitable CA technologies for farmers (especially small- and medium-scale farmers) using irrigated production systems, CIMMYT agronomists have been working with NARSs and the farmers themselves, especially in south Asia, Central Asia, and Mexico, to develop appropriate CA technologies for surface irrigated wheat-based production systems. As a result of this effort, there are now over 3 million ha of irrigated wheat seeded without tillage or with much reduced tillage in the Indo-Gangetic Plains of India and Pakistan; a large proportion of this land is managed by small farmers (Gupta and Sayre 2007). Although direct-seeded wheat is generally followed by intensively tilled, puddled rice, and farmers remove considerable amounts of crop residues for other uses (animal feed, fuel, etc.), it does represent a major step toward appropriate CA technologies and shows that small- and medium-scale farmers in developing countries can benefit from CA.

## Implications for Future Research

Adoption of new, improved cultivars without parallel changes in soil management to rectify soil problems may simply allow an ephemeral preservation or moderate increases in existing yield levels that may lead to further soil degradation. If systems agronomy does not generate sustainable systems, then investment in breeding will not be effective. The response to the use of virtually all input factors, including fertilizer, water, labor, and mechanization, and the adoption of improved crop cultivars will continue to gradually decrease over time (decreases in both partial and total factor productivities), making it necessary to apply higher amounts of most production factors to simply maintain existing yield levels. Many policy makers and scientists erroneously believe that important agronomy problems have been solved; however, changed conditions (new crops, new agrochemicals, decreasing water and land, climate change, etc.) demand a new generation of crop management research. There is need for a new wheat revolution based on integrated CA farming systems including improved varieties as a component.

One of the major lessons learned from past and present experience is that to achieve complex system changes, many coordinated activities focused on stimulating and supporting farmer experimentation are needed. These activities would necessarily be conducted by CIMMYT in collaboration with local partners (including both governmental and non-governmental institutions and, especially, farmers) to ensure that successful CA technologies and methodologies, once identified, are widely incorporated and promoted. Essential components for successful adoption by farmers include: community awareness programs; training for farmers, researchers, and extension agents; on-farm participatory demonstration plots; on-farm and on-station strategic research combined with well developed adaptive research; equipment development and evaluation; stimulation of local production of adapted equipment; and support for farmer-to-farmer exchange and study visits. Regular monitoring and evaluation of advances and farmer perceptions, and adjustments in response to them, would help ensure a dynamic and successful development process. Understanding farmer perceptions and the limitations to adoption will allow us to analyze the effects of policy (at community, district, regional, and national levels) and discuss with policy makers potential policy shifts to encourage the adoption of sustainable agricultural practices. Because of this multi-faceted approach, activities would be concentrated in a few defined locations rather than spread over a wide area, but at a lower intensity, to overcome the initial lag phase of adoption. These locations will serve as hubs for the surrounding areas. As indicated above, there is a pressing need to further develop and extend CA-based technologies in irrigated wheat areas, where they will have positive impact as a result of increased water and input use efficiency, reduced costs, and increased risk alleviation, as well as adaptation to and mitigation of climate change. In rainfed areas, CA will reduce risks associated with land and soil degradation, which lead to inefficient use of already unpredictable and decreasing rainfall and to fertility decline.

### Crop residue management

A major issue for CA adoption is that crop residue management has consistently involved considerable residue removal for livestock feed. Although the value of crop residue as fodder is widely recognized and relatively easy to assess, its value as a soil protection and improvement measure has not yet been quantified. This quantification would require analyzing the agronomic and economic trade-offs between the use of residue for fodder, for soil protection/improvement, and the production of alternative fodder. The goal of residue management in CA is to balance the optimal level of ground cover (based on soil, climatic, and other associated factors) with the amount of crop residues available and their alternative economic uses (such as for livestock feed). However, little empirical information is available to determine the optimal level of ground cover that guarantees soil benefits, and the agronomic value of retaining more crop residues in the field, especially under more diversified rotations that include strategic forage crops.

Future strategic research will have to concentrate on G x S interactions and the physiological basis of yield potential in different management systems. Historically, new varieties have facilitated wider adoption of new management practices, and changes in management have facilitated wider adoption of new varieties. However, little has been done through genetics and breeding to fully realize new varieties' higher yield potential when sown under CA. Other strategic research will have to focus on nitrogen cycling, water use efficiency, phytopathology and integrated pest management, development of multi-crop, multi-use implements, and adaptation to and mitigation of climate risk through CA. Therefore, hubs should be implemented, especially in areas where direct impact can be achieved because of current soil and environmental degradation (e.g., the cotton-wheat system in Uzbekistan), the high pressure on land (e.g., the maize-wheat system in China), the increased costs of inputs (e.g., in the rice-wheat system in India), and the potential for crop diversification (e.g., all of the above systems). If coordinated efforts are made to apply this strategy, CA adoption should be a reality in over 80% of the wheat-based systems in these prime focus environments by 2025. Thus, wheat will continue to be a major staple food for billions of inhabitants around the world.

However, there are clear indications that the rate of increase in wheat yield in many farmers' fields in both developed and developing countries is slowing down. Many farmers are compelled to use ever-increasing levels of costly inputs simply to maintain current yield levels. Obviously, the generation of new, improved cultivars by plant breeders would positively contribute to remedy this situation. But unless major research investments are made to develop and transfer appropriate and cost-effective crop systems management technologies that lead to sustainable and adoptable systems such as CA, the real yield potential will not be reached, and the global role of wheat will be at risk.

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# Reality on the Ground: Integrating Germplasm, Crop Management, and Policy for Wheat Farming System Development in the Indo-Gangetic Plains

**O. Erenstein**

## Introduction

Wheat production systems in South Asia have been transformed over the last 40 years starting with the Green Revolution in the 1960s. The technological packaging of improved wheat seed, chemical fertilizer, and irrigation in an overall supportive infrastructural and policy environment for agricultural transformation led to rapid wheat productivity growth. For instance, in India, average wheat yields have more than tripled over the last 40 years, and wheat yield growth thereby was the highest among all principal crops. Yield increase was the main source of wheat production growth during the 1980s, but it decelerated in the 1990s, and has been relatively stagnant since the turn of the century. The stagnation in wheat productivity, continued population growth, and diversification incentives have put increasing pressure on India's self-sufficiency in wheat, leading to wheat imports during the last two years and putting wheat back on the political agenda (Chand 2007).

Wheat production in South Asia is concentrated in the Indo-Gangetic Plains (IGP), where it is primarily grown in rice-wheat systems under irrigated conditions (Timsina and Connor 2001). The Green Revolution markedly intensified the rice-wheat systems in the IGP, but these later became a victim of their own success, with degradation of the natural resource base widely seen as the root cause of the recent stagnation in productivity growth and growing water scarcity. The agricultural development community faces the challenge of sustaining crop productivity gains, improving rural livelihoods, and securing environmental sustainability in the IGP. This calls for a better understanding of farming systems and rural livelihoods.

## The Farming System and Livelihood Base

The IGP can be divided broadly into eastern and western sub-regions (Erenstein et al. 2007c). The eastern sub-region (East [E] Uttar Pradesh [UP], Bihar, and West [W] Bengal in India; the Nepal terai; and W Bangladesh) has problems of poor water control and flooding; rainfed (monsoon/*kharif*) lowland rice is the traditional cereal staple and the mainstay of food security. Only in recent decades have wheat and other cool season crops been introduced on a large scale in the east, north of the tropic of Cancer. In contrast, the western sub-region (Punjab, Haryana, and W UP in India; Punjab in Pakistan) is mainly semi-arid and would be water scarce were it not for its irrigation infrastructure (canals and groundwater tube-wells). In the western plains, winter/*rabi* wheat has traditionally been, and continues to be, the mainstay of food security. In recent decades, there has been a major increase in the area of rice grown in the monsoon/*kharif* season. Another important contrast is that, whereas in the eastern IGP cattle are the predominant livestock, in the western IGP, buffalo dominate. In broad terms, therefore, the eastern IGP is characterized by rural livelihoods based on rice-cattle farming systems, while rural livelihoods in the western IGP are based on wheat-buffalo farming systems. Therefore, although the IGP is a contiguous area, there are significant gradients and variations between sub-regions. The sheer size of the IGP also implies that each sub-region assumes national/regional prominence: the northwest (NW) IGP and the terai are the granary for Pakistan, India, and Nepal; UP is India's most populous state; Bihar is one of India's poorest states; W Bengal and Bangladesh are the most densely populated Indian state and country, respectively.

In the Indian IGP, the aggregate asset base is markedly more favorable in the NW IGP and declines proceeding to the eastern plains of Bihar. Particularly marked are the larger farm size, larger herd size, and more widespread mechanization and irrigation in the NW IGP. In contrast, rainfall and population density increase proceeding to the E IGP, as does the incidence of poverty (Erenstein et al. 2007c; Erenstein et al. 2007b). Wealth is closely associated with access to land in rural communities across the IGP, where smallholders and the landless poor predominate; large farmers are markedly concentrated in the NW IGP (Erenstein et al. 2007c). The west-east asset gradient in the IGP also has pronounced effects on prices of resources such as land and labor, which are both much higher in the NW IGP. The institutional environment also tends to be more favorable in the NW IGP. Women's role in agriculture increases as one proceeds eastward. Gender inequity is still a major issue reflected inter alia by gendered wage rates and lower female literacy (Erenstein et al. 2007c).

Livelihood strategies predominantly revolve around crop-livestock systems and farm labor throughout the IGP, but with significant west-east gradients (Erenstein et al. 2007c). Wheat is the dominant food/feed crop in the NW IGP, whereas rice is dominant in the eastern plains. Rice-wheat is the dominant cropping pattern in the NW IGP, and cropping systems become more diversified towards the east (Erenstein et al. 2007c). For instance, in the rice-wheat belts of India and Pakistan in the NW IGP, rice and wheat crops occupy three-fourths of the cultivated area (Erenstein et al. 2007c; Farooq et al. 2007). Cereal production in the NW IGP is more market oriented, reflecting larger surplus production (Erenstein et al. 2007c).

Livestock ownership is widespread and complements the rice and wheat based cropping systems as the basis of rural livelihoods. In the Indian IGP, herd size shows a striking inverse relationship with prevailing poverty levels (Erenstein et al. 2007c). Livestock are generally stall-fed throughout the year. Wheat straw is the preferred basal ruminant feed in the NW IGP, while rice straw is preferred in the east; this is linked to tradition and the availability of mechanical threshers for wheat. The preferred cereal straws have scarcity value and are intensively collected, stored, and used as the basal animal feed; occasional surpluses are traded. However, despite the importance of straw as feed, grain yield remains the main consideration in farmers' varietal choice. Stubble grazing shows a marked west-east gradient in the IGP, from low levels in the northwest to high levels in the eastern plains (Erenstein et al. 2007c). In the NW IGP, seasonal cultivation of fodder crops is common, but fodder cultivation declines towards the eastern plains (Erenstein et al. 2007c; Farooq et al. 2007).

Throughout the Indian IGP, crop production appears as the main source of livelihood for landed households, with livestock typically complementary and, to a large extent, dependent on the crop enterprise (Erenstein et al. 2007c). In the rice-wheat belts of India and Pakistan in the NW IGP, rice and wheat provide the lion's share of household income, which is supplemented by livestock raising (Erenstein et al. 2007a). Landless households depend primarily on their labor assets, with livestock making an important contribution (Erenstein et al. 2007c). In the Indian IGP, there is also a marked gradient in the reliance on temporary labor: hiring temporary labor for crop operations is the rule in the NW, but this decreases as one proceeds eastward to the Bihar sub-region, where small farms and family labor predominate.

The diverging agricultural history of the IGP sub-regions has led to significant variations in terms of poverty alleviation and agricultural productivity. Rural development indicators in the Indian states of Punjab and Haryana in the NW IGP now compare well with those of middle income countries (World Bank 2006). Yet large tracts of the IGP, despite their agricultural potential, remain mired in poverty. The main example of this is the E IGP, an area with 500 million people, characterized by smallholders and widespread poverty (>30% below the official poverty line; more than two-thirds of the population survive on less than US$ 2 a day).

## Wheat–Poverty Linkages

The situation described above has important implications in terms of wheat–poverty linkages. First, there is an inverse relationship between the relative extent of wheat cultivation in the farming system and rural poverty in the IGP. Second, within any wheat producing locality, there is a marked gradient that goes from wheat being a major contributor to household income (on large farms) to wheat being a major household expense (for the landless). This implies that the poverty alleviation potential of general wheat cultivation enhancement is primarily indirect, through lower wheat prices for poor wheat consumers. Third, there has been a tendency for wheat R&D efforts to focus on larger farmers and the NW IGP. Direct poverty alleviation would imply targeting wheat cultivation enhancement efforts to the specific wheat production constraints of smallholders in general and the pocket of poverty in the E IGP in particular.

A techno-centric approach and the inherent diversity among stakeholders has often resulted in only partial stakeholder analysis, if any. Agricultural scientists have increasingly started to recognize the need to acknowledge the differential resource base of IGP target groups—yet boundaries between who is considered a large farmer and who a smallholder are often blurred; more worryingly, the implications for the landless are often forgotten. The larger farmer clientele typically demands labor-saving technologies, but these inherently shift income from laborers to producers. Both large and small farmers may ostensibly benefit from labor-saving technologies, and may actually need them to remain competitive, enhance productivity, and make a decent living from farming. However, landless laborers typically lose out in the absence of alternative employment at the local level and lack the skills to gain remunerative employment elsewhere. The gender segmentation in the labor market imposes further social costs. The implications also cut across IGP sub-regions, with the intensive northwestern systems still relying on migrant labor from the eastern plains to alleviate their labor peaks. This calls for a better understanding of livelihood implications and broader stakeholder dialogue/participation in technology development. In the end, it also calls for remedial action outside the immediate agricultural development sphere, both in terms of making non-agricultural economic growth more labor-intensive and enhancing primary rural education to provide the rural poor with the minimum human capital needed to escape poverty (Erenstein 2006).

## System Dynamics and Technological Change

Current farm systems in the IGP are predominantly small-scale, integrated, crop-livestock systems and likely to remain so in the medium term to 2020. Continuing fragmentation of land holdings implies an increasing reliance on off-farm income sources. Marginal farmers will likely continue to move out of agriculture only where sufficient and appropriate alternative income-generating opportunities exist, as has been the case in the NW IGP in India, thereby allowing for some consolidation of farm size. The few farmers with large landholdings who seem to be moving towards crop specialization have the means to invest in mechanization and thereby circumvent labor bottlenecks. Further specialization in commercial dairy farming is likely for those who have sufficiently large dairy enterprises and secure market access. Such specialization, more likely in the peri-urban interface, would also imply an increasing spatial separation between livestock production and feed production, and greater reliance on and development of crop residue and fodder markets (Erenstein et al. 2007c).

A striking feature of a recent village survey was the apparent stagnation of rural communities across the Indian IGP in this post-Green Revolution period (Erenstein et al. 2007c). Many communities gave the impression that they were waiting to be helped, exhibiting a strong dependence on hoped-for government intervention and demonstrating a lack of personal initiative. Another striking feature of these communities was the lack of shocks having widespread impact on the rural population (Erenstein et al. 2007c).

In terms of technological change, zero- and reduced-tillage wheat have spread rapidly in the rice-wheat systems of the IGP since the turn of the century, to an estimated 1.6 million ha by 2004/05 in India (Laxmi et al. 2007). Central to the new technology is the zero-tillage drill (ZTD), a mechanical tractor-mounted seed drill that can sow wheat into an untilled rice field. Recent studies confirmed widespread adoption of zero-tillage (ZT) wheat in the rice-wheat belt of the NW IGP (Erenstein et al. 2007a). More recently, ZT has also started to pick up in the eastern plains.

Developing adequate input value chains for ZTDs, from factory to farmer fields, proved crucial to reducing tillage in the NW IGP (Seth et al. 2003). The private sector recognized that ZT offered a substantial market opportunity, and local manufacturing capacity was developed to produce, adapt, and deliver ZTDs to farmers at a competitive cost. The close links of scientists and farmers to private manufacturers, which included providing machines to villages for farmer experimentation, allowed rapid feedback and refinement of the implements. In India, strong support from state and local government officials, including the provision of a subsidy to lower investment costs, helped disseminate the technology. The Rice-Wheat Consortium (RWC) for the IGP (www.rwc.cgiar.org) played a catalytic role in promoting the public-private partnership, nurtured it through its formative stages, and facilitated technology transfer from international and national sources. Accessibility to the ZTD was greatly enhanced by ZTD service providers (Erenstein et al. 2007a), who had the added advantage of having hands-on experience and a clear incentive to promote the technology. The concerted efforts of a range of stakeholders thus proved crucial to developing ZTD input value chains for the farmer.

The main driver behind the rapid and widespread acceptance of ZT is the combination of a significant continuing “yield effect” and a substantial “cost-saving effect,” which ensure the immediate profitability of adoption, particularly in Haryana, India (Erenstein et al. 2007a). The resource base and livelihood strategy of farm households have also proved particularly influential: zero tillage adoption is closely associated with farm size, asset base, and specialization in the rice-wheat system (Erenstein et al. 2007a). The significant wheat area of ZT adopters implies larger annual benefits, lower relative learning costs, and earlier payback of ZTD investment.

So far, ZT has primarily been adopted for the wheat crop in rice-wheat systems. For the full environmental impact of ZT to materialize, the R&D community faces the challenge of extending reduced tillage to the rice crop and retaining crop residues as mulch on the soil surface (Gupta and Sayre 2007; Hobbs 2007). Reducing tillage for the subsequent rice crop is still problematic and presents additional challenges, although such an initiative could benefit from the existing machinery and information value chains (Erenstein 2006). Prevailing crop residue management practices are still largely incompatible with residue retention, not least due to the widespread use of wheat residue as feed and the burning of rice residues in the NW IGP (Erenstein et al. 2007c).

## Implications for Research

Water is a major concern for the sustainability of cropping systems throughout the IGP and for the South Asian economy as a whole. Water management concerns vary from over-exploitation of groundwater in some areas to poor, unreliable irrigation and the negative effects on productivity from flooding and waterlogging in others (Erenstein et al. 2007c). With the continuing spread of private diesel-powered tube and shallow wells, declining water tables are likely to become more widespread and require urgent study to inform policy making and short- and medium-term action planning. In fact, this is one area where policy adjustments are essential to complement water use efficient varieties and production practices. Resource conservation technologies such as ZT can improve field-scale irrigation efficiency, but these savings do not necessarily translate into "real" water savings (Ahmad et al. 2007; Humphreys et al. 2005). In any event, irrigation water savings with ZT in wheat are still modest, particularly when compared to potential savings in rice. To address the impending water crisis, the R&D community urgently needs to enhance water productivity of the rice component of the rice-wheat system and tackle some of the more thorny policy issues, such as the subsidy and support schemes that currently undermine the sustainability of rice-wheat systems (Erenstein et al. 2007a).

Soil fertility and organic matter mining pose another threat to current livelihood strategies in the IGP. Organic matter management is particularly problematic, with the largely one-way extractive flows from the field leading to depletion of soil organic matter stocks throughout the IGP, particularly in the eastern plains. The prevailing crop residue management practices, intensive use of cereal residues, and limited application of farmyard manure mean that few organic residues remain in the field at the time of land preparation. Soil fertility is further undermined by unbalanced fertilizer use (Erenstein et al. 2007c). Research and development efforts need to address this challenge, including research to determine the minimum amounts of crop residues that should be retained and to develop appropriate alternative feed sources and crop residue management practices, along with adequate policy measures.

The prevalence of single wheat varieties over large contiguous areas (e.g., PBW 343 in India and Inqalab-91 in Pakistan; Erenstein et al. 2007a) is another worrying issue given the underlying risk from any resistance breakdown. Cool, moist weather can trigger yellow rust and leaf rust epidemics in the IGP (Nagarajan 2004). The risks have become even more pressing in view of the general susceptibility of prevailing varieties to new stem rust races virulent for wheat (UG99, Mackenzie 2007; Raloff 2005); this poses a major threat to wheat production throughout the IGP in the immediate future. The recently established Global Rust Initiative (www.globalrust.org) urgently needs further support to mitigate the impending impact of Ug99 in South Asia.

Wheat is a temperate crop grown during the cool winter season in the IGP. Proceeding to the eastern plains, the winter season becomes progressively shorter, thereby limiting the potential productivity of wheat. Limited water control often implies delays in the rice crop, further retarding wheat establishment. In the Indian IGP, this contributes to a situation where actual wheat productivity is highest in the NW IGP and then decreases by some 100 kg per ha for every 100 km eastwards (Nagarajan 2004). In West Bengal and Bangladesh, current productivity levels increasingly undermine wheat's competitiveness against alternative winter crops such as winter maize. Global warming will exacerbate heat stress for wheat and have far-reaching consequences for its cultivation across the IGP (Hodson et al. this volume). Research is urgently needed to develop appropriate coping strategies.

Despite the above threats and the overall stagnation in wheat yield growth in the IGP, there is still scope for enhancing wheat productivity (e.g., Reynolds et al. 2007). The main opportunities for reinvigorating wheat yield growth in the IGP lie in the traditional sources of productivity growth: improved varieties and crop management to push out the wheat yield frontier and narrow the yield gap. Improved varieties will also play a major role in tackling the above threats—particularly through higher irrigation water productivity, drought tolerance, durable stem rust resistance, and heat tolerance. In the eastern plains, there is also an increased need for appropriate short-cycle germplasm.

Improved crop management practices offer particular scope to enhance the expression of genetic potential, save resources and costs, and raise wheat competitiveness. In the previous section, mention was already made of resource-conserving technologies such as ZT and their adoption by farmers. Late planting of wheat is still a major cause of reduced wheat yields in rice-wheat systems. Terminal heat implies that wheat yield potential diminishes by 1-1.5% per day if planting occurs after mid-November (Ortiz-Monasterio et al. 1994; Hobbs and Gupta 2003). Zero tillage has the potential to alleviate late planting of wheat, as it substantially reduces the turn-around time between the rice and wheat crops. However, a recent survey in NW IGP found no significant difference in terms of time of wheat establishment between ZT and conventional plots (Erenstein et al. 2007a). This suggests farmers have generally been reluctant to significantly advance the wheat sowing date despite apparently increased opportunities to do so with ZT. Still, wheat productivity within rice-wheat systems will receive a boost when conservation agriculture principles of reduced tillage and mulch are extended to the entire cropping system. Zero tillage can also be seen as a step towards permanent bed-planting systems with further advantages for wheat yields and water and cost savings (Gupta and Sayre 2007).

It is important for R&D to generate appropriate improved varieties and crop management practices, but in so doing, it needs to increasingly select improved varieties under conservation agriculture conditions so as to exploit GxE interactions. Conservation agriculture also has important risk-reducing implications through its potential to conserve water and reduce soil temperature oscillations—aspects particularly important given the water scarcity and climate change implications.

Diversification represents both an opportunity and a threat to the wheat farming systems of the IGP. In India, output value chains in the NW IGP are characterized by widespread public intervention, particularly assured produce prices and marketing channels for rice and wheat grain. Although these chains fostered intensification, they now represent a major obstacle to the diversification of rice-wheat systems. Minimum support prices for "fair average quality" also provided no incentive for better grain quality (Nagarajan 2004). The combination of secure produce markets and irrigation meant that rice and wheat production was a low-risk activity that, until recently, was difficult to displace. However, forces are transforming the playing field in the Indian IGP. Liberalization has opened up wheat and rice markets to new private players and put upward pressure on wheat prices (Chand 2007). The public sector thereby had to resort to grain imports for the last two years to procure enough wheat for its public distribution system, which covers those under the poverty line. India's rapidly evolving domestic market implies new opportunities for diversifying rice-wheat systems with selected vegetables, legumes, feed/fodder crops, and livestock products (Gulati et al. 2007). Still, rice and wheat continue to provide the greatest share of calories, especially for the rural poor, the sharp decline in their share of expenditures during the 1990s notwithstanding (Ray 2007). Diversification options, being labor intensive and small scale, tend to have a positive poverty-reduction bias. Finally, wheat productivity will receive a boost when rice-wheat systems become more diversified and include alternative monsoon crops. Targeted R&D efforts are needed to facilitate this diversification and address the immediate challenges and opportunities for wheat producers and wheat consumers, both within and beyond the IGP.

In conclusion, the rice-wheat systems in the IGP have long exemplified South Asia's agricultural transformation through the Green Revolution, which combined improved varieties, better crop management, and enabling policies. The same systems now also exemplify post-Green Revolution stagnation and challenges, despite receiving considerable attention from the R&D and policy community.

The apparent homogeneity of vast irrigated plains masks significant diversity and underlying gradients in assets, livelihood strategies, and livelihood outcomes. Zero-tillage wheat is one of the few recent examples of widespread positive technological change in the IGP. However, further R&D and policy efforts are needed in the IGP—first, to address threats such as the impending water crisis, soil fertility mining, the new virulent stem rust race, and global warming; second, to realize opportunities for reinvigorating wheat yield growth, enhancing wheat competitiveness, and diversifying to high value crops and livestock. There is also scope to extend rice-wheat R&D achievements such as ZT and/or initiate targeted R&D activities in other wheat systems, particularly cotton-wheat, maize-wheat, and rainfed wheat systems in South Asia.

In the end, though, wheat R&D in the IGP would benefit from a paradigm shift. The change will involve a shift from reductionist, plot-level research to people-centered, participatory, and holistic methods and to inter-disciplinary, multi-institutional approaches that link farmers, technology, and policy. Only by integrating technology (both improved varieties and crop management) and policy/institutions will we be able to sustain crop productivity gains, improve rural livelihoods, and secure the environmental sustainability of the wheat farming systems of the IGP.

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# Profiles of wheat in nine countries

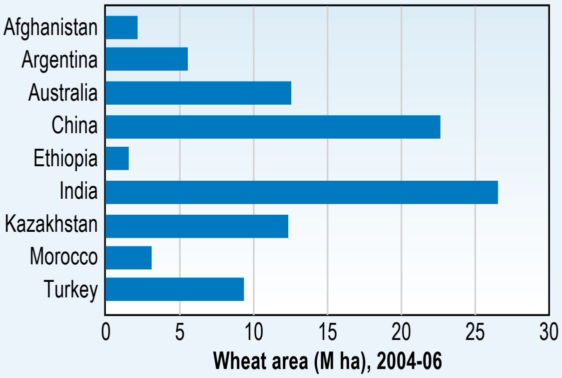
To depict the diversity of wheat production systems and issues, this section provides profiles of wheat in nine countries—Afghanistan, Argentina, Australia, China, Ethiopia, India, Kazakhstan, Morocco, and Turkey—of differing environments, potentials, and constraints and which together account for 40% of the world's wheat production. The selection covers differing levels of economic development, rainfed and irrigated wheat production settings, strong presence of the private sector or none, lowland and highland ecologies, and use of conservation agriculture versus traditional practices. Sources of the information are as follows: [1] Mahmood Osmanzai, CIMMYT wheat agronomist (based in Afghanistan), personal communication; [2] FAOSTAT, 20 February 2008; [3] FAOSTAT, November 2007; [4] from CIMMYT databases, surveys, and contacts. Finally, we thank the following contributors: Mohammed Jlibene (Morocco), Nathan Leamy (USA), Francisco Margiotta (Argentina), Miguel Mendez (Argentina), Rubén Miranda (Argentina), Jan Nyssen (Belgium), and Richard Trethowan (Australia).

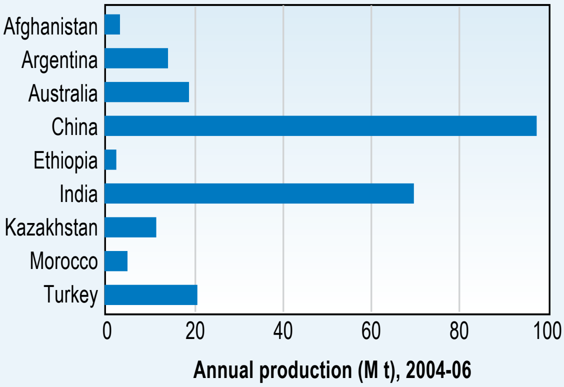
**AFGHANISTAN** Military and civil conflicts have caused recurring problems throughout the country. In 2005 the agricultural population formed approximately 65% and the rural population 76% of the Afghan population [2]. Average farm size is estimated at 1-2 ha. Land is relatively evenly divided between irrigated and rainfed crops. Wheat is increasingly grown in rotation with maize, rice, pulses, or melons. Debt is widespread, with 60% of farmers owing money in 2003. [1]

*Wheat quality standards*. Most wheat is used for small artisan bakeries. Quality for export or industrialization has taken a back seat to production. White grain is preferred.

Due to the lack of suitable farm implements, *conservation agriculture* practices have not been adopted, but efforts have been made to reduce traditional land preparation. National *biotechnology* capacity is very low.

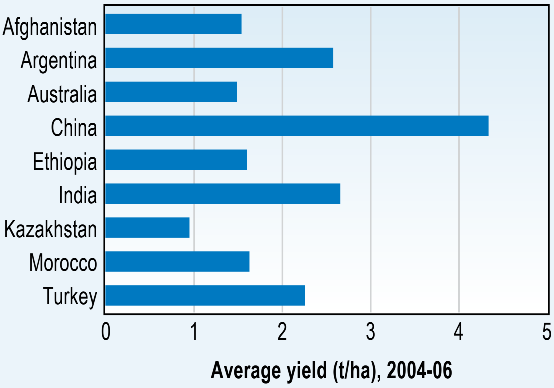
*Climate change* appears to be affecting the wheat growing season: higher temperatures have been reported.

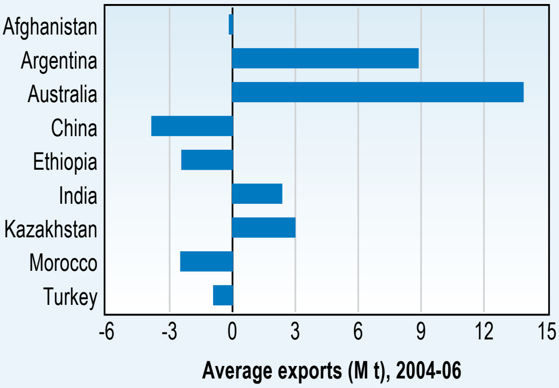




**ARGENTINA** In 2005 the agricultural population formed about 9% and rural population 10% of the total Argentinian population [2]. The average size for rainfed farms in Argentina is around 450 ha, but varies significantly. The main cropping system is wheat rotated with soybean. Other crops in rotations include maize, sunflower, sorghum, and, to a lesser extent, barley, oats, sunflower. In the Pampas, the crop-pasture system is common. [4]

*Wheat quality standards*. Argentina still focuses predominantly on yields and output. A recently-developed classification system for wheat quality has not been implemented; current standards are based on grain physical characteristics, soundness, and dockage. The flour produced in Argentina is used mainly in small bakeries, with very little utilized in industrial bread products; demand for high-gluten wheat is low, but some companies have begun exporting wheat with differentiated quality (protein content), particularly to Brazil. Average wheat consumption in Argentina during 2003–2005 was 320 g/capita/day [3].





Argentinean farmers have adopted *conservation agriculture* practices on about 60% of wheat lands, in some regions up to 90%. Area under zero-tillage in 2004-05 was over 18 million hectares. Argentina's farmers are strong supporters of *biotechnology*: nearly 95% of soybeans and 40% of maize grown are genetically modified varieties.

*Effects of climate change* on wheat in Argentina are likely to be mixed or uncertain, but the overall tendency may be negative.

**AUSTRALIA** In 2005 the agricultural population formed only about 4% and the rural population 7% of the total Australian population [2]. Grazing and rainfed cropping farms are around 2,500 ha on average—smaller in high-rainfall areas and much larger in low-rainfall areas. Irrigated farms in cropping areas are relatively few and average around 490 ha, although irrigation is used mainly for horticultural crops. Typical cropping systems are wheat / fallow (in very dry areas), and wheat/barley/legume and or oilseed in many other areas, although wheat/pasture is also common.[4]

*Wheat quality standards*. Australia is a consistent supplier of quality and high-protein wheat. Wheat is classified based on seed hardness, dough strength, and extensibility at fixed protein levels. Because recent droughted and hot seasons have reduced protein quality, researchers are working to develop drought/heat tolerant wheat with consistent quality. Average wheat consumption in Australia during 2003–2005 was 186 g/capita/day [3].

Large areas are under *conservation agriculture* practices, including about two-thirds of cropped lands—some 9 million ha—under reduced or zero-tillage. Australia is a world leader in breeding and *biotechnology*.

Effects of *climate change* in Australia are likely to vary by region. Negative effects due to increasing temperatures and declining rainfall are likely to be most pronounced in the western and southern wheat growing areas. Conversely, northern and eastern wheat regions may exhibit moderate increases in wheat production depending on the extent of positive effects of $CO_2$ fertilization.

**CHINA** In 2005 the the agricultural population formed about 64% and rural population 59% of the total Chinese population [3]. The average farm size is 1.2 ha for rainfed farms and 0.7 ha for irrigated farms; many households have both irrigated and rainfed plots. Farm size has been decreasing. Winter wheat/maize rotation is dominant in north China on both irrigated and rainfed land, although irrigated land predominates. Spring-planted single crop wheat systems are also practiced in northeastern and northwestern China. Wheat/maize, wheat/maize/beans (including soybeans), and wheat/rice systems are found in southwestern China. [4]

*Wheat quality standards*. China has seen an increased demand for higher quality and greater consistency in its flour in recent years with the shift driven largely by changes in domestic consumption patterns away from noodles and steamed breads towards leavened breads and ready-made foods. The government has increased priority on research to improve and disseminate wheat quality. The National Grain Bureau, with the Ministry of Agriculture, is creating a national standard for wheat quality. Millers can currently contract directly with farmers to cultivate higher quality wheat for purchase, often paying 10-20% higher price. Average wheat consumption in China during 2003–2005 was 164 g/capita/day [3]. Standards are on the way.

*Conservation agriculture* and *biotechnology* are both being developed.

*Effects of climate change* in China are likely to vary by wheat growing environment, but vitally important will be the extent to which beneficial effects of $CO_2$ fertilization can be realized. Without any $CO_2$ fertilization effect, yield declines are predicted throughout most of the Chinese wheat areas. Conversely, with full $CO_2$ fertilization effects, yield gains are predicted for most of the major wheat growing areas. In the irrigated areas, maximum benefits from $CO_2$ fertilization will only occur if sufficient water and nutrients are available. Spring wheat areas in the north may be impacted from increasing heat stress, whereas winter wheat areas may benefit from reduced risk of frost.

**ETHIOPIA** In 2005 the agricultural population formed about 80% and the rural population 84% of the Ethiopian population. [2] About 90% percent of households are less than 1 ha, with the largest households having just 3 ha. Wheat is usually grown as a monocrop.

*Wheat quality standards*. Ethiopia's wheat production splits 60:40 between bread wheat and durum. Many farmers grow low-yield wheat because of the high cost of seed of improved cultivars. Because of low grain quality, prices and demand are low for Ethiopian wheat. Average wheat consumption in Ethiopia during 2003–2005 was 103 g/capita/day. [3]

There has been resistance to the use of *conservation agriculture* techniques as part of the promoted integrated watershed management, because of competition for residue to feed cattle or for fuel and construction. There is currently no capacity in *biotechnology*.

Ethiopian wheat area is largely delimited by temperature; hence, increasing temperatures from *climate change* are likely to increase heat stress and reduce the area suitable for wheat.

**INDIA** In 2005 the agricultural population formed about 51% and rural population 71% of the total Indian population [2]. The average farm size is shrinking on irrigated land, but in both irrigated and rainfed systems remains between 1 and 2 ha. Typical cropping systems include rotations such as rice-wheat, maize-wheat, maize-potato-wheat, cotton-wheat, sugar cane-wheat.[4]

*Wheat quality standards*. Increased mechanization of baking and branded flour for Chapatti in India requires more consistent wheat quality. Currently, emphasis on yields remain high. Raising protein quality is an important breeding objective both for increased demand within the domestic market and for international sale. Informal and regional wheat markets in India are currently the most effective controls for the quality of Indian wheat, because existing policies often provide disincentives to improve wheat quality at a national level. Average wheat consumption in India during 2003–2005 was 171 g/capita/day [3].

*Conservation agriculture* is on the way, despite competition for the use of residues. India is on the verge of becoming a major player in the *biotechnology sector* in the region.

*Climate change effects* in India are likely to vary somewhat by region, but the overall tendency for wheat production is likely to be negative. Lower potential productivity areas are most likely to be negatively effected, as warming will likely increase the area experiencing heat stress.

**KAZAKHSTAN** In 2005 the agricultural population formed about 18% and the rural population 44% of the Kazakh population [2]. The average farm size has a considerable range but is generally shrinking. Large farms, predominantly in the north, can be up to 100,000 ha. Peasant farms range in size from 500 to 1,000 ha. Typical cropping systems include rotations such as fallow-wheat-wheat, fallow-wheat-wheat-barley, fallow-wheat-wheat-barley-wheat, fallow-wheat-wheat-wheat. Irrigated wheat area is 100,000 ha. The average farm size for irrigated wheat crops is 180 ha. [4]

*Wheat quality standards*. Standards are not updated to present markets. Farmers in Kazakhstan produce large amounts of high-protein wheat, although the quality of that protein is generally low. Kazakhstani wheat is generally well-regarded and sought by millers in the region. Efforts are ongoing to increase yields and gluten protein composition. Average wheat consumption in Kazakhstan during 2003–2005 was 392 g/capita/day [3].

Strong commitments from the Kazakhstani Ministry of Agriculture have begun efforts to convert larger portions of their farmland to *conservation agriculture* practices in coming years. Almost 21% of farmland is under minimal tillage. Efforts are underway to build stronger, more flexible linkages among *biotechnology* scientists, wheat breeders, and end-users.

*Climate change effects*—particularly warming—are likely to be positive for wheat production.

**MOROCCO** In 2005 the agricultural population formed about 33% and the rural population 41% of the Moroccan population [2]. The average size for rainfed farms in Morocco is 5 ha; irrigated farms average around 2 ha. Typical cropping systems are wheat-cereal, wheat-legumes, and wheat-sunflower. Wheat is almost universally associated with sheep production, with the straw used as feed. [4]

*Wheat quality standards*. Two-thirds of Moroccan wheat is bread wheat; the remainder, durum wheat. Large amounts of grain are used in the poultry industry. Durum wheat is used primarily for pasta and couscous, although some is used in leavened and flat bread. Much of the remaining bread wheat is used in small bakeries to manufacture flat and leavened breads. Of greater importance than protein quality to Moroccan farmers are higher yields and drought tolerance. Average wheat consumption during 2003–2005 was 520 g/capita/day [3].

*Conservation agriculture* methods were introduced in the 1980s, but few Moroccan farmers are using them. Morocco is a strong collaborator with CIMMYT in developing *biotechnology*. The country faces numerous challenges in adapting wheat that will better serve its needs.

*Climate change effects* are likely to be negative for wheat production.

**TURKEY** In 2005 the agricultural population formed about 28% and the rural population 33% of the Turkish population [2]. The average size of a rainfed farm in Turkey is estimated at around 4.8 ha and 2 ha for an irrigated farm, but farm size is highly variable. Both types of farm are on a shrinking trend. Typical cropping systems include rotations such as wheat-fallow and wheat-food legumes systems in the winter wheat areas and wheat-cotton and wheat-maize in spring wheat areas. [4]

*Wheat quality standards*. Turkey has a well-established flour industry to supply the large consumption of wheat bread products. Gluten quantity and quality will continue to be of great importance, as well as yellow color score for the production of durum wheat and resulting pasta. Average wheat consumption in Turkey during 2003–2005 was 476 g/capita/day [3].

Turkey has yet to pursue extensive use of *conservation agriculture* methods, though there have been experimental plots tested. The country hopes to build a strong *biotechnology* program, but has to consider the high investment costs.

Given the range of environments and conditions for wheat production in Turkey, *climate change effects* are likely to be mixed and uncertain.

# Selected Wheat Statistics

**P. Aquino and F. Carrión**

The following tables present statistics on wheat production, trade, utilization, type of wheat, prices, and input use. These statistics reflect the latest information available at the time of publication.

Countries are classified as either "developing" or "high-income" based on the criteria used by the World Bank in its World Development Indicators (2001). Countries classified as developing had a per capita gross national income (GNI) lower than US$ 9,265 in 1999, whereas high-income countries had a per capita GNI exceeding US$ 9,266. Countries in Eastern Europe and the Former Soviet Union (FSU) are treated separately. Traditionally included as "developed" countries in FAO statistics, most of these countries would be classified as developing countries by World Bank criteria.

The first set of tables is divided into two sections: production statistics and consumption statistics. Developing countries and those in Eastern Europe and the FSU are included in individual country statistics if they produced (or consumed) at least 100,000 tons of wheat per year. Developing countries are included in the production statistics section if they produced more than 100,000 tons of wheat per year, regardless of their import and consumption levels. Developing countries that produced less than 100,000 t/yr, but at least 50% of their total wheat consumption, are also listed in the production statistics section. Other developing countries that consumed over 100,000 t/yr are included in the consumption statistics section. High-income countries are classified in the same way, using a minimum level of production or consumption of one million tons. A three-year average of the latest data available was used in the classification.

Unless otherwise indicated, regional aggregates include data from all the countries in a particular region, including those countries for which data were not reported individually. Regional means are appropriately weighted, and so they may not exactly equal the mean of the average values presented for each country. Former Czechoslavakia, Former Yugoslavia, and the FSU were divided into separate countries, for which statistics were reported individually.

## Notes on the Variables

The data source for all production and consumption statistics is FAOSTAT (2007). Growth rates were calculated using the log-linear regression model:

$$\text{In } Y = \alpha + ßt + \varepsilon,$$

where In Y is the natural logarithm of Y, t is time period (year), $\alpha$ is a constant, ß is the growth rate of Y, and $\varepsilon$ is the error term. The function describes a variable Y, which displays a constant proportional rate of growth (ß>0) or decay (ß<0). ß may be interpreted as the annual percentage change in Y.

Yield was computed by dividing three-year average production by the three-year average area harvested, which gives an average weighted by areas in the different years. The data source is FAOSTAT Production Statistics (2007).

Net imports are defined as the amount of imports minus exports. The data source is FAOSTAT Trade Statistics (2007).

Total consumption was calculated as the sum (in kilograms) of the amounts used for each type of wheat utilization (i.e., food, feed and seed, and other net uses). The data source is FAOSTAT Commodity Balances (2007). The growth rate was calculated using the regression model given above.

Data on wheat type, prices, and input use were collected through a general country survey of knowledgeable wheat scientists. Data on prices and input use refer to an important producing region within each country. The wheat price is the average post-harvest price received by farmers. The fertilizer price is usually the price paid by farmers for the most common fertilizer. In a few cases, data were estimated by CIMMYT staff based on secondary sources.

# Production Statistics

| Region / Country | Average wheat area, yield, and production, 2003-05 | | | Growth of wheat area (%/yr) | | | |
|---|---|---|---|---|---|---|---|
| | Harvested area (000 ha) | Yield (t/ha) | Production (000 t) | 1951-66 | 1966-79 | 1980-94 | 1995-05 |
| **Eastern and Southern Africa** | **2,735** | **1.8** | **4,982** | **2.1** | **0.3** | **-1.5** | **-0.1** |
| Ethiopia[a] | 1,398 | 1.5 | 2,034 | 1.0 | -6.5 | <1 | 5.8 |
| Kenya | 154 | 2.4 | 376 | -0.9 | -0.7 | 2.9 | 0.2 |
| South Africa | 793 | 2.1 | 1,756 | 3.1 | 2.6 | -4.6 | -5.0 |
| Sudan | 160 | 2.3 | 365 | 8.4 | 11.7 | 8.4 | -8.2 |
| Zambia | 25 | 4.7 | 119 | n.a. | 29.0 | 13.5 | 11.1 |
| Zimbabwe | 42 | 3.9 | 164 | 4.0 | 17.2 | 0.9 | -2.2 |
| **North Africa** | **7,170** | **2.3** | **16,752** | **-0.1** | **0.3** | **1.1** | **1.2** |
| Algeria | 1,887 | 1.4 | 2,703 | 0.2 | 0.3 | -2.9 | 1.0 |
| Egypt | 1,137 | 6.5 | 7,403 | -1.8 | 0.3 | 4.4 | 1.1 |
| Libya | 165 | 0.8 | 125 | 1.5 | 2.1 | -5.8 | 0.3 |
| Morocco | 3,006 | 1.5 | 4,577 | 0.7 | -0.8 | 3.7 | 1.9 |
| Tunisia | 974 | 1.8 | 1,778 | -1.5 | 2.4 | -0.9 | 0.9 |
| **West Asia** | **22,388** | **2.1** | **47,408** | **2.5** | **1.0** | **1.0** | **0.5** |
| Afghanistan | 2,145 | 1.6 | 3,346 | 1.3 | 0.6 | -0.8 | -0.1 |
| Iran | 6,570 | 2.1 | 13,980 | 5.0 | 0.7 | 1.1 | 0.4 |
| Iraq | 1,934 | 1.1 | 2,130 | 0.7 | -0.9 | 3.3 | 3.2 |
| Lebanon | 46 | 2.7 | 124 | -0.2 | -3.0 | 4.2 | 6.4 |
| Saudi Arabia | 510 | 5.2 | 2,649 | 6.6 | -0.3 | 16.5 | 4.7 |
| Syria | 1,844 | 2.6 | 4,706 | -0.1 | 4.0 | 0.8 | 1.2 |
| Turkey | 9,233 | 2.2 | 20,336 | 2.6 | 1.2 | 0.5 | -0.2 |
| Yemen | 84 | 1.2 | 105 | 6.0 | 8.4 | 2.8 | -2.5 |
| **South Asia** | **35,721** | **2.6** | **92,934** | **2.1** | **3.4** | **0.8** | **0.1** |
| Bangladesh | 635 | 2.0 | 1,245 | 3.5 | 8.8 | 1.4 | -1.2 |
| India | 26,107 | 2.7 | 69,953 | 2.3 | 4.1 | 0.6 | 0.2 |
| Myanmar | 103 | 1.3 | 136 | 14.5 | -1.7 | 2.8 | <1 |
| Nepal | 670 | 2.1 | 1,391 | -1.1 | 8.0 | 3.7 | 0.4 |
| Pakistan | 8,203 | 2.5 | 20,098 | 1.7 | 1.2 | 1.1 | -0.1 |
| **East Asia** | **22,398** | **4.1** | **91,919** | **-0.1** | **1.4** | **0.4** | **-3.6** |
| China[b] | 22,139 | 4.2 | 91,594 | -0.29 | 1.5 | 0.4 | -3.6 |
| Mongolia | 175 | 0.7 | 145 | 24.7 | 0.8 | 1.4 | -8.3 |
| North Korea | 81 | 2.5 | 170 | 8.7 | -6.0 | 0.5 | 0.2 |
| **Mexico, Central America, and the Caribbean** | **593** | **4.5** | **2,695** | **1.0** | **-0.7** | **0.3** | **-4.4** |
| Mexico | 586 | 4.6 | 2,684 | 1.1 | -0.8 | 0.5 | -4.3 |
| **Andean Region, South America** | **275** | **1.2** | **337** | **-0.2** | **-3.2** | **0.9** | **-1.6** |
| Bolivia | 110 | 1.1 | 119 | 6.5 | 3.1 | 1.2 | -3.2 |
| Peru | 131 | 1.4 | 180 | -0.5 | -2.9 | -0.2 | 2.4 |
| **Southern Cone, South America** | **9,037** | **2.5** | **22,780** | **0.3** | **2.1** | **-2.0** | **-2.6** |
| Argentina | 5,590 | 2.6 | 14,366 | 1.1 | -0.5 | -2.0 | -0.3 |
| Brazil | 2,576 | 2.2 | 5,544 | -1.3 | 12.0 | -2.6 | 8.0 |
| Chile | 419 | 4.4 | 1,857 | -0.1 | -2.1 | -0.2 | 1.2 |
| Paraguay | 302 | 2.0 | 598 | 12.7 | 4.1 | 8.1 | 4.7 |
| Uruguay | 151 | 2.8 | 415 | -3.8 | -0.8 | -3.1 | -4.7 |
| **Eastern Europe and Former Soviet Union[c]** | **53,124** | **2.1** | **113,747** | **0.4** | **-1.0** | **-1.7** | **0.5** |
| Albania | 85 | 3.0 | 258 | 1.0 | 4.0 | -2.2 | -5.9 |
| Armenia | 126 | 2.0 | 257 | ++ | ++ | ++ | 5.2 |
| Azerbaijan | 597 | 2.6 | 1,537 | ++ | ++ | ++ | 3.5 |
| Belarus | 338 | 3.0 | 1,030 | ++ | ++ | ++ | 4.2 |
| Bosnia Herzegovina | 80 | 3.0 | 243 | ++ | ++ | ++ | 1.4 |
| Bulgaria | 994 | 3.2 | 3,148 | -1.7 | -1.5 | 1.5 | -0.4 |
| Croatia | 189 | 3.6 | 684 | ++ | ++ | ++ | -1.5 |

| Growth of wheat yield (%/yr) | | | | Growth of wheat production (%/yr) | | | | Wheat area as percent of total cereal area (average), 2003-05 (%) |
|---|---|---|---|---|---|---|---|---|
| 1951-66 | 1966-79 | 1980-94 | 1995-05 | 1951-66 | 1966-79 | 1980-94 | 1995-05 | |
| **0.1** | **3.5** | **2.9** | **1.4** | **2.2** | **3.9** | **1.4** | **1.3** | **7** |
| 2.0 | 2.7 | 2.3 | 1.7 | 3.0 | -3.8 | 2.3 | 7.5 | 15 |
| 1.2 | 1.1 | -1.2 | 2.8 | 0.3 | 0.4 | 1.7 | 2.9 | 8 |
| -1.9 | 4.2 | 3.9 | 2.7 | 1.1 | 6.8 | -0.7 | -2.3 | 18 |
| -0.3 | -1.1 | 1.9 | 3.6 | 8.0 | 10.6 | 10.3 | -4.7 | 2 |
| n.a. | 8.0 | 2.3 | -1.6 | n.a. | 37.0 | 15.8 | 9.4 | 4 |
| 6.4 | 4.1 | 0.9 | -0.2 | 10.4 | 21.3 | 1.9 | -2.4 | 3 |
| **1.3** | **1.2** | **4.5** | **2.8** | **1.2** | **1.5** | **5.5** | **3.9** | **55** |
| -0.9 | <1 | 2.4 | 4.5 | -0.7 | 0.3 | -0.5 | 5.5 | 69 |
| 2.3 | 2.6 | 4.0 | 1.9 | 0.5 | 2.9 | 8.4 | 3.0 | 40 |
| 9.0 | 3.3 | 3.8 | -0.7 | 10.5 | 5.4 | -2.0 | -0.5 | 47 |
| 1.8 | 1.5 | 2.0 | 4.6 | 2.5 | 0.7 | 5.7 | 6.5 | 54 |
| 4.4 | <1 | 2.3 | 3.5 | 2.9 | 2.4 | 1.3 | 4.4 | 67 |
| **-0.3** | **3.1** | **1.8** | **2.1** | **2.2** | **4.0** | **2.8** | **2.6** | **67** |
| -0.1 | 1.8 | -1.8 | 3.7 | 1.2 | 2.4 | -2.6 | 3.6 | 77 |
| -1.3 | 2.7 | 3.4 | 2.9 | 3.8 | 3.4 | 4.4 | 3.3 | 73 |
| 1.5 | -1.2 | -0.8 | 4.5 | 2.2 | -2.1 | 2.5 | 7.7 | 60 |
| 1.5 | 1.7 | 4.1 | 3.1 | 1.3 | -1.4 | 8.3 | 9.4 | 76 |
| 1.3 | 0.9 | 4.9 | 2.1 | 7.9 | 0.5 | 21.4 | 6.8 | 76 |
| 1.8 | 3.0 | 3.6 | 1.8 | 1.7 | 7.0 | 4.4 | 3.0 | 58 |
| -0.6 | 3.8 | 0.7 | 1.3 | 2.0 | 4.9 | 1.2 | 1.1 | 67 |
| 0.5 | -1.5 | 4.6 | -1.7 | 6.5 | 6.9 | 7.5 | -4.2 | 13 |
| **1.1** | **4.0** | **2.8** | **1.1** | **3.2** | **7.3** | **3.6** | **1.2** | **27** |
| 0.9 | 7.5 | -1.0 | -0.5 | 4.3 | 16.3 | 0.4 | -1.7 | 6 |
| 1.4 | 3.8 | 3.2 | 0.7 | 3.7 | 7.9 | 3.9 | 1.0 | 27 |
| 4.4 | 2.5 | -2.7 | 5.3 | 18.9 | 0.8 | <1 | 5.3 | 1 |
| 2.1 | -0.2 | 0.8 | 3.9 | 1.1 | 7.8 | 4.5 | 4.3 | 20 |
| 0.5 | 4.3 | 1.7 | 2.1 | 2.2 | 5.6 | 2.8 | 2.0 | 65 |
| **0.9** | **5.0** | **3.3** | **1.3** | **0.7** | **6.4** | **3.8** | **-2.4** | **27** |
| 0.9 | 5.0 | 3.4 | 1.2 | 0.6 | 6.5 | 3.8 | -2.4 | 28 |
| 2.8 | 2.1 | 0.4 | -1.1 | 27.5 | 2.9 | 1.8 | -9.4 | 97 |
| -7.8 | 8.1 | 0.3 | 5.5 | 0.9 | 2.2 | 0.7 | 5.7 | 6 |
| | | | | | | | | |
| **7.3** | **3.5** | **0.4** | **1.6** | **8.3** | **2.9** | **0.7** | **-2.8** | **4** |
| 7.3 | 3.7 | 0.2 | 1.6 | 8.4 | 2.8 | 0.8 | -2.7 | 6 |
| **0.7** | **<1** | **1.6** | **1.4** | **0.5** | **-3.2** | **2.5** | **-0.2** | **5** |
| 0.1 | 1.5 | 2.4 | 2.5 | 6.5 | 4.6 | 3.5 | -0.7 | 14 |
| 0.1 | 1.0 | 2.0 | 1.5 | -0.5 | -1.9 | 1.8 | 3.9 | 12 |
| **1.7** | **1.0** | **2.7** | **5.6** | **1.9** | **3.1** | **0.7** | **3.0** | **24** |
| 1.8 | 3.1 | 2.0 | 1.4 | 2.9 | 2.5 | <1 | 1.1 | 42 |
| -0.4 | -0.6 | 3.8 | 2.9 | -1.7 | 11.4 | 1.2 | 10.9 | 13 |
| 1.9 | -0.7 | 6.2 | 2.5 | 1.9 | -2.7 | 6.0 | 3.6 | 61 |
| 1.4 | 0.9 | 2.2 | 1.7 | 14.1 | 5.0 | 10.3 | 6.5 | 39 |
| 0.2 | 0.9 | 3.7 | <1 | -3.6 | 0.1 | 0.6 | -4.7 | 29 |
| | | | | | | | | |
| **2.8** | **2.1** | **1.8** | **2.2** | **3.2** | **1.0** | **0.1** | **2.7** | **53** |
| -0.2 | 5.5 | -0.5 | 2.1 | 0.8 | 9.5 | -2.7 | -3.9 | 57 |
| ++ | ++ | ++ | -0.6 | ++ | ++ | ++ | 4.6 | 64 |
| ++ | ++ | ++ | 6.4 | ++ | ++ | ++ | 9.9 | 76 |
| ++ | ++ | ++ | 3.4 | ++ | ++ | ++ | 7.6 | 16 |
| ++ | ++ | ++ | -0.8 | ++ | ++ | ++ | 0.6 | 24 |
| 3.1 | 2.8 | -1.8 | 2.6 | 1.4 | 1.3 | -0.3 | 2.2 | 58 |
| ++ | ++ | ++ | -0.1 | ++ | ++ | ++ | -1.7 | 29 |

# Production Statistics (continued)

| Region / Country | Average wheat area, yield, and production, 2003-05 | | | Growth of wheat area (%/yr) | | | |
|---|---|---|---|---|---|---|---|
| | Harvested area (000 ha) | Yield (t/ha) | Production (000 t) | 1951-66 | 1966-79 | 1980-94 | 1995-05 |
| Czech Republic | 777 | 5.1 | 3,942 | ++ | ++ | ++ | -0.5 |
| Czechoslovakia | ++ | ++ | ++ | n.a. | 2.3 | 0.5 | ++ |
| Estonia | 77 | 2.6 | 202 | ++ | ++ | ++ | 6.3 |
| Georgia | 105 | 1.9 | 200 | ++ | ++ | ++ | 2.0 |
| Hungary | 1,139 | 4.1 | 4,679 | -2.1 | 0.4 | -2.0 | 0.1 |
| Kazakhstan | 11,514 | 0.9 | 10,781 | ++ | ++ | ++ | 1.0 |
| Kyrgyzstan | 421 | 2.3 | 987 | ++ | ++ | ++ | -0.4 |
| Latvia | 177 | 3.1 | 548 | ++ | ++ | ++ | 3.5 |
| Lithuania | 354 | 3.8 | 1,338 | ++ | ++ | ++ | 1.3 |
| Macedonia | 104 | 2.9 | 305 | ++ | ++ | ++ | -1.9 |
| Moldova Republic | 309 | 2.2 | 673 | ++ | ++ | ++ | -3.2 |
| Poland | 2,279 | 3.9 | 8,841 | 0.4 | -0.2 | 4.2 | -1.1 |
| Romania | 2,035 | 2.9 | 5,877 | 0.7 | -2.3 | -0.5 | -0.2 |
| Russian Federation | 22,536 | 1.9 | 42,405 | ++ | ++ | ++ | 0.7 |
| Serbia and Montenegro | 604 | 3.4 | 2,046 | ++ | ++ | ++ | -2.5 |
| Slovakia | 349 | 4.1 | 1,434 | ++ | ++ | ++ | -1.7 |
| Slovenia | 33 | 4.2 | 137 | ++ | ++ | ++ | -0.8 |
| Tajikistan | 326 | 2.0 | 641 | ++ | ++ | ++ | 2.6 |
| Turkmenistan | 857 | 3.1 | 2,640 | ++ | ++ | ++ | 6.8 |
| Ukraine | 4,854 | 2.7 | 13,273 | ++ | ++ | ++ | -1.6 |
| USSR | ++ | ++ | ++ | n.a. | -1.1 | -2.4 | ++ |
| Uzbekistan | 1,473 | 3.8 | 5,581 | ++ | ++ | ++ | 1.1 |
| Yugoslavia, SFR | ++ | ++ | ++ | n.a. | -1.6 | 0.1 | ++ |
| **Western Europe, North America, Japan and other high-income countries** | **61,920** | **3.5** | **214,447** | **-0.1** | **0.7** | **-1.2** | **-0.7** |
| Australia | 13,030 | 1.9 | 24,376 | 5.1 | 1.3 | -3.6 | 2.7 |
| Austria | 284 | 5.1 | 1,454 | 2.5 | -0.8 | -1.3 | 1.5 |
| Belgium-Luxembourg[d] | 218 | 8.5 | 1,847 | 1.0 | -1.1 | 1.2 | 0.1 |
| Canada | 10,052 | 2.5 | 25,396 | 1.1 | -0.1 | 0.2 | -1.9 |
| Denmark | 669 | 7.2 | 4,782 | 4.2 | 1.8 | 10.4 | <1 |
| Finland | 214 | 3.5 | 754 | 5.2 | -4.8 | -2.3 | 7.9 |
| France | 5,129 | 7.0 | 35,669 | 0.1 | 0.4 | 0.1 | 0.4 |
| Germany | 3,083 | 7.4 | 22,793 | 1.5 | 1.7 | 0.6 | 2.1 |
| Greece | 848 | 2.3 | 1,946 | 1.5 | -1.2 | -0.6 | -0.2 |
| Ireland | 98 | 8.9 | 870 | -4.3 | -4.5 | 2.8 | 2.6 |
| Italy | 2,248 | 3.3 | 7,528 | -0.8 | -2.3 | -2.7 | -0.9 |
| Japan | 213 | 4.1 | 864 | -2.8 | -11.8 | -0.7 | 4.0 |
| Netherlands | 135 | 8.7 | 1,176 | 5.1 | -1.8 | -0.9 | -0.1 |
| New Zealand | 40 | 7.2 | 290 | 5.6 | -1.7 | -6.9 | -3.0 |
| Norway | 81 | 4.8 | 384 | -13.0 | 19.0 | 11.1 | 3.0 |
| Spain | 2,192 | 2.6 | 5,734 | -0.2 | -4.2 | -1.9 | 1.0 |
| Sweden | 390 | 5.9 | 2,314 | -3.4 | 2.7 | -0.2 | 2.6 |
| Switzerland | 88 | 5.7 | 502 | 0.8 | -1.84 | 0.9 | -1.6 |
| United Kingdom | 1,899 | 7.8 | 14,879 | 0.2 | 2.8 | 1.6 | -0.39 |
| United States of America | 20,664 | 2.9 | 59,944 | -1.9 | 2.3 | -1.4 | -2.7 |
| **Regional aggregates** | | | | | | | |
| Developing countries | 100,429 | 2.8 | 279,190 | 1.1 | 1.8 | 0.5 | -0.8 |
| Eastern Europe and Former Soviet Union | 53,124 | 2.1 | 113,747 | 0.4 | -1.0 | -1.7 | 0.5 |
| Western Europe, North America, Japan, and other high-income countries | 61,920 | 3.5 | 214,447 | -0.1 | 0.7 | -1.2 | -0.7 |
| World | 215,494 | 2.8 | 607,429 | 0.5 | 0.5 | -0.6 | -0.5 |

Note: ++ = not applicable; n.a. = not available.

[a] Data for Ethiopia include figures for Ethiopia PDR (1951-1992).

[b] Data for China include figures for Mainland, Hong Kong, Taiwan and Macao.

[c] Data for 1993-05 (Former Czechoslovakia), 1992-05 (Former Soviet Union and Former Yugoslavia).

[d] Data for Belgium-Luxembourg include figures for Belgium and Luxembourg.

| Growth of wheat yield (%/yr) | | | | Growth of wheat production (%/yr) | | | | Wheat area as percent of total cereal area (average), 2003-05 (%) |
|---|---|---|---|---|---|---|---|---|
| 1951-66 | 1966-79 | 1980-94 | 1995-05 | 1951-66 | 1966-79 | 1980-94 | 1995-05 | |
| ++ | ++ | ++ | 1.2 | ++ | ++ | ++ | 0.7 | 50 |
| n.a. | 3.2 | 1.4 | ++ | n.a. | 5.5 | 1.9 | ++ | ++ |
| ++ | ++ | ++ | 3.3 | ++ | ++ | ++ | 9.5 | 29 |
| ++ | ++ | ++ | 4.3 | ++ | ++ | ++ | 6.3 | 31 |
| 2.7 | 4.5 | -0.5 | 0.6 | 0.6 | 4.9 | -2.5 | 0.6 | 39 |
| ++ | ++ | ++ | 4.8 | ++ | ++ | ++ | 5.9 | 84 |
| ++ | ++ | ++ | 1.8 | ++ | ++ | ++ | 1.4 | 71 |
| ++ | ++ | ++ | 3.6 | ++ | ++ | ++ | 7.1 | 39 |
| ++ | ++ | ++ | 4.4 | ++ | ++ | ++ | 5.7 | 39 |
| ++ | ++ | ++ | 0.9 | ++ | ++ | ++ | -1.0 | 53 |
| ++ | ++ | ++ | -3.7 | ++ | ++ | ++ | -6.9 | 29 |
| 3.8 | 2.7 | 1.1 | 1.5 | 4.2 | 2.4 | 5.3 | 0.4 | 27 |
| 2.9 | 3.7 | -0.2 | 0.6 | 3.5 | 1.4 | -0.7 | 0.4 | 36 |
| ++ | ++ | ++ | 3.2 | ++ | ++ | ++ | 3.9 | 57 |
| ++ | ++ | ++ | 0.6 | ++ | ++ | ++ | -1.9 | 30 |
| ++ | ++ | ++ | -0.8 | ++ | ++ | ++ | -2.5 | 44 |
| ++ | ++ | ++ | 0.7 | ++ | ++ | ++ | -0.1 | 33 |
| ++ | ++ | ++ | 6.7 | ++ | ++ | ++ | 9.2 | 83 |
| ++ | ++ | ++ | 10.6 | ++ | ++ | ++ | 17.5 | 87 |
| ++ | ++ | ++ | -0.3 | ++ | ++ | ++ | -1.9 | 37 |
| n.a. | 1.6 | 2.9 | ++ | n.a. | 0.5 | 0.5 | ++ | ++ |
| ++ | ++ | ++ | 7.8 | ++ | ++ | ++ | 8.8 | 87 |
| n.a. | 2.9 | 2.5 | ++ | n.a. | 1.2 | 2.6 | ++ | ++ |
| | | | | | | | | |
| **2.2** | **1.7** | **1.8** | **0.7** | **2.1** | **2.4** | **0.6** | **0.1** | **46** |
| 1.0 | 1.6 | 2.7 | -1.6 | 6.2 | 2.8 | -1.0 | 1.0 | 65 |
| 2.3 | 1.7 | 1.4 | <1 | 4.9 | 0.9 | <1 | 1.5 | 35 |
| 1.3 | 2.8 | 2.2 | 0.8 | 2.3 | 1.7 | 3.5 | 0.9 | 64 |
| 0.3 | 1.3 | 1.2 | 0.7 | 1.4 | 1.2 | 1.3 | -1.2 | 58 |
| 1.0 | 1.3 | 1.5 | -0.2 | 5.2 | 3.2 | 11.9 | -0.2 | 45 |
| 1.3 | 1.3 | 1.6 | -0.3 | 6.5 | -3.4 | -0.7 | 7.6 | 18 |
| 3.4 | 2.9 | 2.0 | 0.3 | 3.5 | 3.3 | 2.1 | 0.7 | 56 |
| 1.4 | 1.9 | 2.2 | 0.4 | 2.9 | 3.6 | 2.8 | 2.5 | 45 |
| 2.8 | 3.4 | -0.3 | -0.9 | 4.3 | 2.2 | -1.0 | -1.0 | 67 |
| 2.1 | 2.0 | 2.2 | 0.8 | -2.2 | -2.5 | 5.0 | 3.4 | 33 |
| 1.8 | 1.1 | 2.0 | 0.5 | 1.0 | -1.2 | -0.7 | -0.4 | 54 |
| 0.8 | 1.6 | 1.4 | 3.1 | -2.0 | -10.2 | 0.7 | 7.2 | 11 |
| 1.3 | 2.8 | 1.5 | 0.3 | 6.4 | 1.0 | 0.6 | 0.2 | 62 |
| 1.6 | 0.1 | 2.6 | 3.6 | 7.1 | -1.6 | -4.3 | 0.6 | 33 |
| 2.4 | 2.6 | -0.3 | 0.2 | -10.6 | 21.6 | 10.8 | 3.2 | 25 |
| 1.1 | 2.6 | 2.1 | 1.7 | 0.9 | -1.6 | 0.2 | 2.7 | 33 |
| 4.3 | 1.7 | 1.6 | 0.2 | 0.9 | 4.4 | 1.4 | 2.8 | 35 |
| 1.4 | 1.93 | 1.8 | -1.2 | 2.2 | 0.1 | 2.7 | -2.8 | 54 |
| 2.8 | 2.1 | 1.3 | 0.11 | 3.0 | 4.9 | 2.9 | -0.3 | 62 |
| 3.3 | 1.2 | 0.4 | 1.2 | 1.4 | 3.5 | -1.0 | -1.5 | 36 |
| | | | | | | | | |
| 0.9 | 3.6 | 2.8 | 1.1 | 1.9 | 5.4 | 3.3 | 0.3 | 22 |
| 2.8 | 2.1 | 1.8 | 2.2 | 3.2 | 1.0 | 0.1 | 2.7 | 53 |
| | | | | | | | | |
| 2.2 | 1.7 | 1.8 | 0.7 | 2.1 | 2.4 | 0.6 | 0.1 | 46 |
| 1.6 | 2.4 | 2.2 | 1.1 | 2.1 | 2.9 | 1.6 | 0.7 | 32 |

# Consumption Statistics

| | Average net wheat imports, 2003-05 | | Wheat consumption | | | | Average percent wheat use, 2003-05 (%) | |
|---|---|---|---|---|---|---|---|---|
| | | | Average per capita, (kg/yr) | | Growth rate per capita, (%/yr) | | | |
| Region / Country | Total (000 t) | Per capita (kg/yr) | 1980-95 | 2003-05 | 1980-95 | 1996-05 | Human consumption | Animal feed |
| **Eastern and Southern Africa** | **6,038** | **16** | **24** | **29** | **0.6** | **2.4** | **83** | **<1** |
| Angola | 56 | 4 | 16 | 36 | -1.9 | 6.8 | 83 | ++ |
| Djibouti | 91 | 116 | 53 | 154 | 4.4 | 5.1 | 61 | ++ |
| Ethiopia[a] | 1,421 | 19 | 26 | 47 | 3.0 | 7.4 | 86 | ++ |
| Kenya | 466 | 14 | 19 | 25 | -0.3 | <1 | 87 | ++ |
| Madagascar | 39 | 2 | 5 | 7 | 3.0 | 0.5 | 80 | ++ |
| Mauritius | 133 | 108 | 81 | 95 | 1.1 | <1 | 84 | ++ |
| Mozambique | 363 | 19 | 12 | 19 | 1.4 | 3.2 | 74 | ++ |
| South Africa | 1,014 | 21 | 66 | 54 | -0.5 | -1.5 | 86 | 1 |
| Sudan | 1,298 | 36 | 32 | 47 | 4.4 | 5.1 | 81 | ++ |
| Tanzania | 442 | 12 | 6 | 13 | -2.3 | 7.4 | 85 | ++ |
| Uganda | 250 | 9 | 2 | 9 | 4.0 | 16.1 | 79 | ++ |
| Zimbabwe | 78 | 6 | 26 | 20 | 0.5 | -8.8 | 76 | ++ |
| **Western and Central Africa** | **5,044** | **14** | **11** | **18** | **-2.3** | **6.4** | **85** | **<1** |
| Cameroon | 274 | 17 | 14 | 19 | 2.3 | 13.2 | 92 | ++ |
| Congo, Dem Republic of | 377 | 7 | 6 | 9 | -2.2 | 9.5 | 68 | ++ |
| Congo, Republic of | 120 | 31 | 34 | 47 | -0.7 | 3.2 | 88 | ++ |
| Côte d'Ivoire | 237 | 13 | 19 | 15 | -2.8 | 0.2 | 94 | ++ |
| Ghana | 311 | 14 | 10 | 19 | 1.8 | 6.1 | 91 | ++ |
| Guinea | 68 | 7 | 13 | 15 | 3.4 | 5.6 | 83 | ++ |
| Liberia | -2 | -1 | 11 | 36 | 2.9 | -4.8 | 95 | ++ |
| Mali | 43 | 3 | 6 | 8 | -3.2 | 1.0 | n.a. | n.a. |
| Mauritania | 205 | 68 | 72 | 101 | 4.2 | -1.5 | n.a. | n.a. |
| Nigeria | 2,847 | 22 | 11 | 24 | -7.6 | 10.5 | 84 | 1 |
| Senegal | 304 | 27 | 21 | 30 | 1.8 | 2.3 | 95 | ++ |
| **North Africa** | **14,593** | **96** | **192** | **212** | **1.0** | **0.3** | **73** | **4** |
| Algeria | 5,300 | 164 | 203 | 252 | 0.9 | 2.9 | 80 | <1 |
| Egypt | 5,232 | 72 | 175 | 175 | 0.8 | -0.7 | 70 | 8 |
| Libya | 402 | 70 | 252 | 261 | 2.9 | -0.5 | 52 | 26 |
| Morocco | 2,472 | 80 | 194 | 225 | 1.0 | <1 | 77 | 6 |
| Tunisia | 1,187 | 119 | 232 | 290 | 0.6 | <1 | 72 | 1 |
| **West Asia** | **6,049** | **22** | **187** | **161** | **-0.5** | **-1.6** | **71** | **3** |
| Iran | 498 | 7 | 202 | 209 | 1.1 | -1.3 | 75 | 12 |
| Iraq | 2,189 | 78 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| Jordan | 556 | 99 | 150 | 116 | -0.5 | -3.8 | 64 | ++ |
| Lebanon | 439 | 124 | 151 | 183 | 0.2 | 2.0 | 71 | 9 |
| Saudi Arabia | 3 | <1 | 100 | 109 | 0.7 | 5.7 | 94 | ++ |
| Syria | -346 | -19 | 212 | 239 | 0.3 | 2.1 | 67 | 9 |
| Turkey | 903 | 13 | 329 | 270 | -1.5 | -1.7 | 63 | 9 |
| Yemen | 1,454 | 72 | 102 | 87 | 3.3 | -6.6 | 92 | ++ |

Note: ++ = not applicable; n.a. = not available.

[a] Data for Ethiopia include figures for Ethiopia PDR (1951-1992).

[b] Data for China include figures for Mainland, Hong Kong, Taiwan and Macao.

[c] Data for 1993-05 (Former Czechoslovakia), 1992-05 (Former Soviet Union and Former Yugoslavia).

[d] Data for Belgium-Luxembourg include figures for Belgium and Luxembourg.

## Consumption Statistics (continued)

| | | | Wheat consumption | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Average net wheat imports, 2003-05 | | Average per capita, (kg/yr) | | Growth rate per capita, (%/yr) | | Average percent wheat use, 2003-05 (%) | |
| Region / Country | Total (000 t) | Per capita (kg/yr) | 1980-95 | 2003-05 | 1980-95 | 1996-05 | Human consumption | Animal feed |
| **South Asia** | **813** | **1** | **61** | **63** | **1.4** | **-1.3** | **83** | **1** |
| Bangladesh | 1,982 | 14 | 27 | 24 | -2.5 | -0.1 | 90 | ++ |
| India | -2,353 | -2 | 60 | 62 | 1.6 | -1.4 | 82 | 1 |
| Myanmar | 85 | 2 | 4 | 5 | -1.6 | 4.0 | 81 | ++ |
| Nepal | 12 | <1 | 39 | 53 | 1.8 | 2.1 | 82 | 1 |
| Pakistan | 144 | 1 | 132 | 127 | 0.8 | -2.3 | 85 | 3 |
| Sri Lanka | 936 | 46 | 42 | 53 | 2.0 | 9.0 | 93 | ++ |
| **Southeast Asia and Pacific** | **10,901** | **22** | **12** | **22** | **3.4** | **4.5** | **81** | **5** |
| Indonesia | 4,150 | 19 | 11 | 21 | 4.2 | 1.4 | 87 | ++ |
| Malaysia | 2,191 | 88 | 39 | 81 | 1.3 | 8.8 | 74 | 8 |
| Philippines | 2,420 | 30 | 21 | 31 | 5.4 | 4.5 | 77 | 16 |
| Thailand | 960 | 15 | 6 | 14 | 9.3 | 5.9 | 85 | ++ |
| Vietnam | 939 | 11 | 6 | 12 | -3.1 | 9.5 | 78 | ++ |
| **East Asia** | **7,709** | **6** | **88** | **72** | **1.4** | **-3.7** | **81** | **<1** |
| China[b] | 3,847 | 3 | 89 | 73 | 1.4 | -3.9 | 82 | 3 |
| Mongolia | 129 | 49 | 263 | 139 | -2.9 | 1.3 | 68 | 3 |
| North Korea | 142 | 6 | 29 | 25 | -2.6 | -1.8 | 80 | 5 |
| South Korea | 3,592 | 75 | 76 | 79 | 3.7 | 3.4 | 63 | 28 |
| **Mexico, Central America and the Caribbean** | **6,106** | **33** | **54** | **50** | **-1.3** | **0.2** | **64** | **4** |
| Costa Rica | 185 | 44 | 42 | 38 | -0.7 | -6.8 | 89 | ++ |
| Cuba | 555 | 49 | 125 | 77 | -3.6 | -0.7 | 56 | 27 |
| Dominican Republic | 329 | 38 | 32 | 40 | 1.1 | 1.8 | 59 | 25 |
| El Salvador | 237 | 35 | 28 | 30 | 1.2 | 2.3 | 89 | ++ |
| Guatemala | 460 | 37 | 27 | 39 | -0.1 | 6.2 | 84 | ++ |
| Haiti | 194 | 23 | 29 | 35 | -0.9 | -0.5 | 95 | ++ |
| Honduras | 167 | 24 | 25 | 33 | 3.4 | 3.3 | 83 | ++ |
| Jamaica | 341 | 129 | 69 | 121 | -0.9 | 6.0 | 86 | ++ |
| Mexico | 3,167 | 30 | 59 | 55 | -1.1 | -0.2 | 57 | 1 |
| Nicaragua | 118 | 22 | 21 | 22 | 1.4 | 2.5 | 86 | ++ |
| Panama | 143 | 45 | 33 | 53 | 2.2 | 3.0 | 85 | ++ |
| Trinidad and Tobago | 128 | 98 | 91 | 97 | -0.8 | 0.5 | 93 | ++ |
| **Andean Region, South America** | **4,554** | **37** | **41** | **41** | **0.2** | **0.2** | **90** | **<1** |
| Bolivia | 213 | 24 | 62 | 46 | 0.2 | -1.6 | 93 | ++ |
| Colombia | 1,225 | 27 | 23 | 27 | 2.2 | 0.5 | 94 | ++ |
| Ecuador | 433 | 33 | 35 | 35 | -2.4 | -1.6 | 90 | <1 |
| Peru | 1,404 | 51 | 55 | 57 | -0.4 | 0.4 | 91 | ++ |
| Venezuela | 1,232 | 47 | 55 | 49 | -0.4 | 0.9 | 87 | <1 |

Note: ++ = not applicable; n.a. = not available.

[a] Data for Ethiopia include figures for Ethiopia PDR (1951-1992).

[b] Data for China include figures for Mainland, Hong Kong, Taiwan and Macao.

[c] Data for 1993-05 (Former Czechoslovakia), 1992-05 (Former Soviet Union and Former Yugoslavia).

[d] Data for Belgium-Luxembourg include figures for Belgium and Luxembourg.

# Consumption Statistics (continued)

| | | | Wheat consumption | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Average net wheat imports, 2003-05 | | Average per capita, (kg/yr) | | Growth rate per capita, (%/yr) | | Average percent wheat use, 2003-05 (%) | |
| Region / Country | Total (000 t) | Per capita (kg/yr) | 1980-95 | 2003-05 | 1980-95 | 1996-05 | Human consumption | Animal feed |
| **Southern Cone, South America** | **-3,784** | **-15** | **75** | **74** | **-0.5** | **-3.0** | **71** | **<1** |
| Argentina | -8,857 | -230 | 151 | 136 | <1 | -7.5 | 57 | 2 |
| Brazil | 4,973 | 27 | 52 | 54 | -0.6 | -1.4 | 81 | 3 |
| Chile | 333 | 21 | 147 | 143 | -0.8 | 0.8 | 79 | 5 |
| Paraguay | -317 | -52 | 61 | 49 | 2.0 | 14.9 | 24 | 51 |
| Uruguay | 84 | 25 | 115 | 153 | -0.3 | <1 | 66 | 2 |
| **Eastern Europe and Former Soviet Union[c]** | **-11,967** | **-30** | **324** | **248** | **-1.4** | **0.7** | **44** | **22** |
| Albania | 322 | 103 | 214 | 221 | 0.5 | -1.3 | 74 | 3 |
| Armenia | 336 | 111 | ++ | 212 | ++ | 5.9 | 73 | 14 |
| Azerbaijan | 949 | 114 | ++ | 316 | ++ | 11.7 | 69 | 8 |
| Belarus | 282 | 29 | ++ | 142 | ++ | 1.8 | 47 | 40 |
| Bosnia and Herzegovina | 338 | 86 | ++ | 170 | ++ | 1.7 | 35 | 31 |
| Bulgaria | -639 | -82 | 443 | 310 | 0.3 | -0.1 | 35 | 36 |
| Croatia | -4 | -1 | ++ | 167 | ++ | -2.3 | 51 | 23 |
| Czech Republic | -778 | -76 | ++ | 308 | ++ | -1.9 | 26 | 44 |
| Czechoslovakia | ++ | ++ | 371 | ++ | 1.7 | ++ | ++ | ++ |
| Estonia | 25 | 19 | ++ | 209 | ++ | 4.0 | 37 | 49 |
| Georgia | 222 | 49 | ++ | 167 | ++ | 1.7 | 54 | 15 |
| Hungary | -1,248 | -123 | 406 | 330 | -1.8 | 0.3 | 26 | 30 |
| Kazakhstan | -2,978 | -201 | ++ | 487 | ++ | 5.9 | 32 | 23 |
| Kyrgyzstan | 82 | 16 | ++ | 245 | ++ | -0.4 | 89 | 2 |
| Latvia | -147 | -64 | ++ | 166 | ++ | -0.9 | 32 | 40 |
| Lithuania | -522 | -152 | ++ | 227 | ++ | -2.6 | 39 | 28 |
| Macedonia | 96 | 47 | ++ | 212 | ++ | -1.8 | 42 | 1 |
| Moldova | 25 | 6 | ++ | 181 | ++ | -2.6 | 40 | 19 |
| Poland | -201 | -5 | 235 | 217 | 0.6 | -1.7 | 46 | 33 |
| Romania | 809 | 37 | 270 | 312 | -0.5 | 8.9 | 50 | 3 |
| Russian Federation | -6,670 | -46 | ++ | 247 | ++ | 0.1 | 45 | 22 |
| Serbia and Montenegro | -270 | -26 | ++ | 168 | ++ | -3.0 | n.a. | n.a. |
| Slovakia | -100 | -19 | ++ | 248 | ++ | -2.8 | 35 | 33 |
| Slovenia | 106 | 54 | ++ | 149 | ++ | 0.7 | 29 | 6 |
| Turkmenistan | 8 | 2 | ++ | 569 | ++ | 16.2 | 41 | 38 |
| Ukraine | -1,930 | -42 | ++ | 226 | ++ | -2.4 | 41 | 19 |
| USSR | ++ | ++ | 356 | ++ | -0.4 | ++ | ++ | ++ |
| Uzbekistan | -120 | -5 | ++ | 213 | ++ | 4.2 | 68 | 4 |
| Yugoslavia SFR | ++ | ++ | 259 | ++ | -0.4 | ++ | ++ | ++ |

Note: ++ = not applicable; n.a. = not available.

[a] Data for Ethiopia include figures for Ethiopia PDR (1951-1992).

[b] Data for China include figures for Mainland, Hong Kong, Taiwan and Macao.

[c] Data for 1993-05 (Former Czechoslovakia), 1992-05 (Former Soviet Union and Former Yugoslavia).

[d] Data for Belgium-Luxembourg include figures for Belgium and Luxembourg.

## Consumption Statistics (continued)

| Region / Country | Average net wheat imports, 2003-05 | | Wheat consumption | | | | Average percent wheat use, 2003-05 (%) | |
|---|---|---|---|---|---|---|---|---|
| | | | Average per capita, (kg/yr) | | Growth rate per capita, (%/yr) | | | |
| | Total (000 t) | Per capita (kg/yr) | 1980-95 | 2003-05 | 1980-95 | 1996-05 | Human consumption | Animal feed |
| **Western Europe, North America, Japan and other high income countries** | **-47,826** | **-53** | **138** | **178** | **1.1** | **0.5** | **46** | **32** |
| Australia | -13,869 | -695 | 193 | 494 | -1.0 | -0.9 | 13 | 15 |
| Austria | -419 | -51 | 121 | 147 | 1.3 | 0.9 | 50 | 25 |
| Belgium-Luxembourg[d] | 2,575 | 237 | 172 | 332 | 2.7 | 1.9 | 21 | 53 |
| Canada | -13,578 | -425 | 237 | 357 | 2.2 | 1.1 | 23 | 30 |
| Denmark | -159 | -30 | 356 | 875 | 11.4 | 2.1 | 10 | 75 |
| Finland | 20 | 4 | 98 | 166 | -2.1 | 5.2 | 47 | 18 |
| France | -15,556 | -258 | 235 | 299 | 1.6 | -0.1 | 27 | 49 |
| Germany | -3,029 | -37 | 165 | 231 | 0.5 | 3.1 | 37 | 48 |
| Greece | 795 | 72 | 192 | 247 | 0.4 | 1.8 | 53 | 16 |
| Ireland | 344 | 84 | 226 | 345 | 3.0 | 2.0 | 27 | 58 |
| Israel | 1,484 | 225 | 189 | 298 | 1.3 | 8.1 | 44 | 34 |
| Italy | 6,550 | 113 | 189 | 202 | -0.2 | 0.4 | 68 | 12 |
| Japan | 5,346 | 42 | 51 | 48 | -0.1 | -0.9 | 89 | 6 |
| Netherlands | 2,914 | 180 | 121 | 256 | 1.9 | 3.9 | 30 | 43 |
| New Zealand | 339 | 85 | 114 | 164 | -0.2 | 1.6 | 57 | 32 |
| Norway | 226 | 49 | 112 | 174 | 0.8 | 2.3 | 68 | 8 |
| Portugal | 1,395 | 134 | 116 | 159 | 2.1 | 0.4 | 60 | 32 |
| Spain | 4,640 | 109 | 138 | 237 | 0.7 | 4.2 | 33 | 55 |
| Sweden | -465 | -52 | 131 | 210 | 4.5 | 1.7 | 36 | 43 |
| Switzerland | 262 | 36 | 126 | 139 | 0.1 | 0.4 | 68 | 16 |
| United Arab Emirates | 919 | 217 | 112 | 186 | 0.3 | -4.8 | n.a. | n.a. |
| United Kingdom | -1,913 | -32 | 188 | 211 | 1.3 | 0.7 | 43 | 47 |
| United States of America | -27,406 | -93 | 117 | 113 | 1.3 | -3.8 | 75 | 11 |
| **Regional aggregates** | | | | | | | | |
| Developing countries | 58,023 | 11 | 69 | 65 | 0.9 | -1.7 | 79 | 6 |
| Eastern Europe and Former Soviet Union | -11,967 | -30 | 324 | 248 | -1.4 | 0.7 | 44 | 22 |
| Western Europe, North America, Japan and other high income countries | -47,826 | -53 | 138 | 178 | 1.1 | 0.5 | 46 | 32 |
| World | - - | - - | 100 | 93 | <1 | -1.0 | 64 | 13 |

Note: ++ = not applicable; n.a. = not available.

[a] Data for Ethiopia include figures for Ethiopia PDR (1951-1992).

[b] Data for China include figures for Mainland, Hong Kong, Taiwan and Macao.

[c] Data for 1993-05 (Former Czechoslovakia), 1992-05 (Former Soviet Union and Former Yugoslavia).

[d] Data for Belgium-Luxembourg include figures for Belgium and Luxembourg.

# Prices of Wheat Seed and Grain

| Region/Country | Farm price of wheat, 2006-07 (US$/t) |  | Consumer price of wheat flour, 2006-07 (US$/t) | Ratio of farm-level fertilizer price to wheat price, 2006-07 |  |  | Fertilized area as a percentage of total wheat area, 2006-07 | Fertilizer applied to wheat, 2006-07 (kg/ha) |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  | Bread | Durum |  | Nitrogen | Phosphorus | Potassium |  | Nitrogen | Phosphorus | Potassium |
| **Eastern and Southern Africa** |  |  |  |  |  |  |  |  |  |  |
| Madagascar | 377 |  | 970 | 10 | 8 | 11 | 70 | 67 | 135 | 98 |
| Rwanda | 482 |  | 909 | 6 | 8 | 8 |  | 350 | 250 | 250 |
| South Africa | 251 | 196 | 480 | 4 |  |  |  | 45 | 12 | 7 |
| Uganda | 227 |  | 909 | 13 | 27 | 27 | 40 | 120 | 60 | 60 |
| Zambia | 317 | 199 | 1,420 | 10 | 7 | 15 | 100 | 186 | 71 | 42 |
| Zimbabwe | 145 |  | 400 | 3 | 3 | 5 | 100 | 166 | 56 | 28 |
| **West Asia** |  |  |  |  |  |  |  |  |  |  |
| Iraq | 170 | 170 | 226 | 5 | 6 |  | 50 | 25 | 50 |  |
| Jordan | 560 | 560 |  |  |  |  |  |  |  |  |
| Turkey | 239 | 246 | 423 | 4 | 8 |  |  | 50 | 80 |  |
| **South Asia** |  |  |  |  |  |  |  |  |  |  |
| Bangladesh | 274 |  | 361 | 1 |  |  | 80 | 85 | 33 | 28 |
| India | 204 | 295 | 346 | 5 | 4 | 5 | 98 | 115 | 49 | 17 |
| Myanmar | 334 |  | 525 | 6 | 6 | 5 |  | 58 | 29 | 19 |
| Nepal | 171 |  | 314 | 7 | 5 | 2 | 90 | 80 | 60 | 20 |
| Pakistan | 169 |  | 220 | 5 | 6 | 0 |  | 113 | 69 |  |
| **East Asia** |  |  |  |  |  |  |  |  |  |  |
| China | 189 |  | 351 | 7 | 6 | 8 | 95 | 279 | 115 | 109 |
| Mongolia | 167 |  | 386 | 67 | 35 |  |  | 60 | 40 | 40 |
| **Mexico, Central America, and the Caribbean** |  |  |  |  |  |  |  |  |  |  |
| Mexico | 198 | 159 | 636 | 5 | 4 |  | 85 | 170 | 50 |  |
| **Andean Region, South America** |  |  |  |  |  |  |  |  |  |  |
| Peru | 157 |  | 379 | 14 | 22 | 24 | 10 | 100 | 46 | 50 |
| **Southern Cone, South America** |  |  |  |  |  |  |  |  |  |  |
| Argentina | 107 | 113 | 319 | 16 | 13 | 21 | 80 | 59 | 42 |  |
| Brazil | 233 |  | 647 | 8 | 9 | 9 |  | 40 | 55 | 40 |
| Uruguay | 170 |  | 710 | 14 | 6 |  | 100 | 40 | 40 |  |
| **Eastern Europe and Former Soviet Union** |  |  |  |  |  |  |  |  |  |  |
| Armenia | 249 |  | 429 | 4 |  |  |  | 120 |  |  |
| Bulgaria | 159 | 212 | 427 | 17 | 21 | 24 | 95 | 175 | 63 |  |
| Czech Republic | 118 |  | 364 | 12 | 20 | 20 |  |  |  |  |
| Georgia | 191 |  | 529 | 11 | 7 | 10 |  | 105 |  |  |
| Hungary | 186 | 197 | 317 | 7 | 9 | 12 | 99 | 120 | 30 | 30 |
| Kazakhstan | 120 | 130 | 485 | 9 | 12 | 17 | 10 | 20 | 20 |  |
| Kyrgyzstan | 118 |  | 263 | 7 | 4 |  |  | 100 | 100 |  |
| Lithuania | 138 |  | 654 | 9 | 11 | 14 |  | 100 | 60 | 60 |
| Poland | 151 |  | 639 | 12 | 11 | 11 |  | 63 | 28 | 33 |
| Tajikistan | 210 | 246 | 478 | 3 | 1 |  |  | 325 | 175 |  |
| Uzbekistan | 240 | 272 | 320 | 1 | 1 |  |  | 325 | 175 |  |
| **Western Europe and other high-income countries** |  |  |  |  |  |  |  |  |  |  |
| Austria | 172 | 185 | 1,056 | 7 | 23 | 23 | 92 | 140 | 50 | 50 |
| Belgium | 204 |  | 680 | 4 | 4 | 3 |  | 200 | 60 | 120 |
| France | 143 | 195 |  | 8 | 12 |  |  | 170 | 55 | 80 |
| Germany | 146 | 239 | 997 | 9 | 14 | 17 | 95 | 180 | 60 | 45 |
| Italy | 173 | 211 | 2,365 | 5 | 6 |  | 100 | 180 | 45 |  |
| Norway | 340 |  | 1,074 | 6 | 29 | 14 | 100 | 165 | 30 | 60 |
| Portugal | 166 | 197 |  | 10 | 13 | 15 |  | 80 | 60 | 40 |
| Spain | 188 | 188 | 1,250 | 7 | 10 | 11 | 95 | 100 | 50 | 50 |
| Switzerland | 659 |  | 2,074 | 4 | 4 | 7 | 97 | 151 | 70 | 90 |

| Ratio of improved seed price to wheat price, 2006-07 | | Farm wage in kg of wheat per day, 2006-07 | Wheat area by type of wheat, 2006-07 (%) | | | | Wheat area under semidwarf wheat verieties, 2006-07 (%) | Wheat area by moisture regime as a percentage of total wheat area, 2006-07 (%) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Spring | | Durum | | | | |
| Bread | Durum | | bread | durum | Winter bread | Winter durum | | Irrigated | Rainfed |
| | | | | | | | | | |
| 2 | | 3 | | | | | | 89 | 11 |
| 1 | | 2 | 100 | | | | 5 | | 100 |
| 3 | 2 | 74 | 99 | 1 | | | 48 | 17 | 83 |
| 4 | | 5 | 100 | | | | 75 | | 100 |
| 3 | | 6 | 100 | | | | 100 | 100 | 0 |
| 2 | | 5 | 100 | | | | 100 | 96 | 4 |
| | | | | | | | | | |
| 1 | 1 | 142 | 50 | 50 | | | | | 100 |
| 1 | 1 | | | | | | | | |
| 1 | 1 | 91 | 59 | 7 | 30 | 4 | 34 | 10 | 90 |
| | | | | | | | | | |
| 1 | | 6 | 100 | | | | 100 | 88 | 13 |
| 2 | 2 | 8 | 97 | 3 | | | 93 | 87 | 13 |
| 1 | | 2 | 100 | | | | 76 | 17 | 84 |
| 3 | | 6 | 100 | | | | 96 | 60 | 40 |
| 1 | | 14 | 100 | | | | 99 | 71 | 29 |
| | | | | | | | | | |
| 1 | | 27 | 21 | | 78 | | 63 | 51 | 50 |
| 2 | | 19 | 100 | | | | | | |
| | | | | | | | | | |
| 2 | 3 | 55 | 90 | 10 | | | 100 | 85 | 15 |
| | | | | | | | | | |
| 5 | | 30 | 10 | 10 | 70 | 10 | | 9 | 91 |
| | | | | | | | | | |
| 2 | 2 | 215 | 95 | 5 | | | 98 | 2 | 98 |
| 2 | | 42 | 100 | | | | 90 | 3 | 98 |
| 2 | | 87 | 100 | | | | | | 100 |
| | | | | | | | | | |
| 1 | | 37 | 2 | | 98 | | 0 | 25 | 75 |
| 2 | 2 | 116 | | | 100 | | 89 | | 100 |
| 3 | | 204 | 8 | | 92 | | 0 | | 100 |
| 2 | | 37 | 1 | 1 | 99 | | 100 | 25 | 75 |
| 1 | 1 | 112 | 1 | | 99 | 1 | | | 100 |
| 2 | 2 | 50 | 0 | | | | 1 | | 100 |
| 1 | | 20 | 29 | | 71 | | | 67 | 33 |
| 1 | | 160 | 14 | | 86 | | 100 | | 100 |
| 3 | | 224 | 17 | | 83 | | 100 | | |
| 1 | 1 | 57 | 37 | | 63 | | 41 | 46 | 54 |
| 2 | 1 | 17 | 4 | | 96 | | | 79 | 21 |
| | | | | | | | | | |
| 3 | 4 | 538 | 3 | 5 | 91 | 1 | 100 | 3 | 97 |
| 4 | | 400 | | | | | | | |
| 4 | 4 | 55 | | | 91 | 9 | | 9 | 91 |
| 4 | 3 | 909 | 1 | | 98 | | 79 | 4 | 96 |
| 3 | 3 | 781 | | | | | | | |
| 3 | | 534 | 70 | | 30 | | 40 | | 100 |
| 3 | 2 | 317 | 92 | 3 | 5 | | 98 | 10 | 90 |
| 2 | 2 | 200 | 68 | 32 | | | 100 | 10 | 90 |
| 2 | | 180 | 2 | | 99 | | | | 100 |

# Farmer Yield and Production Costs for Bread Wheat Using Commercial Seed

| Region/ Country | Technology | Yield (mt/ha) | Production costs (US$/ha) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Seed | Fertilizer | Agrochemicals | Soil preparation | Harvest | Irrigation | Labor | Other | Total |
| **Eastern and Southern Africa** | | | | | | | | | | | |
| Madagascar | Conventional | 2.0 | 97 | 280 | 5 | | 22 | 17 | 11 | 11 | 443 |
| Rwanda | Conv. and min. tillage [d] | 4.5 | 47 | 327 | 22 | 131 | 91 | | 142 | | 760 |
| South Africa | Minimum tillage | 3.0 | 21 | 73 | 55 | 111 | 28 | 28 | 118 | | 433 |
| South Africa | Conventional | 2.4 | 51 | 63 | 32 | 51 | 31 | | 51 | | 278 |
| Uganda | Conventional [d] | 2.0 | 91 | 76 | | 91 | 61 | | 30 | 30 | 379 |
| Zambia | Minimum tillage [d] | 7.0 | 122 | 314 | 29 | 40 | 95 | 86 | 51 | 71 | 808 |
| Zambia | Conventional | 6.0 | 235 | 306 | 47 | 71 | 118 | 118 | 24 | 71 | 988 |
| Zimbabwe | Conventional | 3.2 | 26 | 53 | 8 | 120 | 133 | 4 | 11 | | 356 |
| **West Asia** | | | | | | | | | | | |
| Iraq | Conventional [a c] | 0.9 | 7 | 17 | 1 | 15 | 35 | | 60 | 8 | 143 |
| Turkey | Conv. and Min. tillage | 2.9 | 75 | 96 | 27 | 171 | 102 | 123 | 65 | 34 | 693 |
| **South Asia** | | | | | | | | | | | |
| Bangladesh | Conventional [d] | 2.2 | 49 | 59 | 5 | 32 | 29 | 40 | 139 | 19 | 371 |
| India | Conventional | 4.2 | 31 | 69 | 55 | 86 | 110 | 12 | 49 | 49 | 461 |
| India | Minimum tillage | 2.3 | 47 | 35 | | 59 | 12 | 71 | 24 | 24 | 271 |
| Myanmar | Conventional [c] | 1.3 | 60 | 111 | 16 | 64 | 28 | 16 | 6 | 6 | 306 |
| Nepal | Conventional | 2.5 | 46 | 143 | 36 | 77 | 29 | 57 | 100 | 71 | 559 |
| Pakistan | Conv. and Min. tillage [d] | 1.5 | 33 | 40 | 25 | 57 | 49 | 25 | 20 | 57 | 307 |
| Pakistan | Conventional | 3.5 | 37 | 78 | 27 | 46 | 104 | 91 | | 208 | 590 |
| **East Asia** | | | | | | | | | | | |
| China | Conventional [d] | 4.4 | 36 | 189 | 20 | 83 | 112 | 78 | 49 | | 569 |
| China | Zero tillage | 4.5 | 59 | 98 | 24 | 98 | 118 | | 118 | | 516 |
| Mongolia | Minimum tillage [c] | 1.2 | 32 | 3 | 2 | 15 | 19 | | 14 | 58 | 142 |
| **Mexico, Central America, and the Caribbean** | | | | | | | | | | | |
| Mexico | Conventional | 4.5 | 89 | 167 | 46 | 114 | 73 | 173 | 68 | | 729 |
| **Andean Region, South America** | | | | | | | | | | | |
| Peru | Conventional [c] | 2.0 | 56 | 72 | 39 | 75 | 71 | 14 | 94 | 42 | 464 |
| **Southern Cone, South America** | | | | | | | | | | | |
| Argentina | Minimum tillage | 4.0 | 26 | 119 | 29 | 6 | 161 | | 32 | | 374 |
| Argentina | Conventional | 3.0 | 23 | 107 | | 56 | 31 | | | 129 | 346 |
| Argentina | Zero tillage [c] | 2.4 | 17 | 49 | 13 | 24 | 27 | | 4 | 41 | 176 |
| Brazil | Zero tillage | 2.3 | 64 | 124 | 123 | 0 | 36 | | 41 | 37 | 426 |
| Uruguay | Minimum tillage | 4.1 | 40 | 90 | 33 | 43 | 33 | | 19 | 144 | 402 |
| **Eastern Europe and Former Soviet Union** | | | | | | | | | | | |
| Armenia | Conventional [c] | 2.1 | 47 | 36 | 15 | 50 | 18 | 30 | 30 | 30 | 256 |
| Bulgaria | Conventional | 4.0 | 60 | 48 | 43 | 67 | 60 | | 10 | 29 | 316 |
| Czech Rep. | Conventional | 6.0 | 73 | 114 | 145 | 127 | 118 | | | | 577 |
| Georgia | Conventional [d] | 2.5 | 88 | 44 | 12 | 92 | 0 | 35 | 88 | 7 | 367 |
| Hungary | Conventional | 4.5 | 82 | 153 | 82 | 109 | 98 | | | | 525 |
| Kazakhstan | Conventional | 1.1 | 25 | 14 | 9 | 20 | 25 | | 5 | 19 | 117 |
| Kyrgyzstan | Conventional | 2.1 | 66 | 24 | 17 | 53 | 32 | 184 | 32 | | 406 |
| Lithuania | Conventional | 3.8 | 77 | 192 | 135 | 196 | 115 | | | | 715 |
| Poland | Conventional | 5.0 | 78 | 182 | 81 | 74 | 71 | | 28 | 114 | 629 |
| Tajikistan | Conventional | 2.0 | 64 | 174 | 23 | 93 | 41 | 14 | 58 | 23 | 490 |
| Uzbekistan | Conventional [a] | 4.7 | 8 | 96 | | 96 | 64 | | 64 | 120 | 448 |

## Farmer Yield and Production Costs for Bread Wheat Using Commercial Seed (continued)

| | | | Production costs (US$/ha) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Region/ Country** | **Technology** | **Yield (mt/ha)** | **Seed** | **Fertilizer** | **Agrochemicals** | **Soil preparation** | **Harvest** | **Irrigation** | **Labor** | **Other** | **Total** |
| **Western Europe, North America, and other high-income countries** | | | | | | | | | | | |
| Austria | Minimum tillage | 6.0 | 79 | 145 | 33 | 125 | 106 | | 119 | 40 | 647 |
| Belgium | Conventional | 9.0 | 113 | 95 | 340 | 136 | | | 27 | 136 | 847 |
| France | Conventional | 8.0 | 78 | 188 | 182 | | | 390 | | | 838 |
| Germany | Minimum tillage | 7.3 | 90 | 53 | 53 | 160 | 160 | | | | 516 |
| Italy | Conventional [b] | 5.5 | 125 | 331 | 122 | 243 | 236 | | 405 | | 1,463 |
| Norway | Conventional | 5.0 | 192 | 215 | 116 | 331 | 165 | | 50 | | 1,068 |
| Portugal | Zero tillage | 3.5 | 82 | 109 | 68 | | 54 | 120 | | 82 | 514 |
| Spain | Conventional [b] | 3.5 | 75 | 75 | 113 | 38 | 38 | | 38 | | 375 |
| Switzerland | Conventional | 6.1 | 339 | 312 | 311 | 586 | 488 | | | 329 | 2,366 |

Notes:

[a] Bread and durum wheat

[b] Durum wheat

[c] Local seed

[d] Commercial and local seed

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