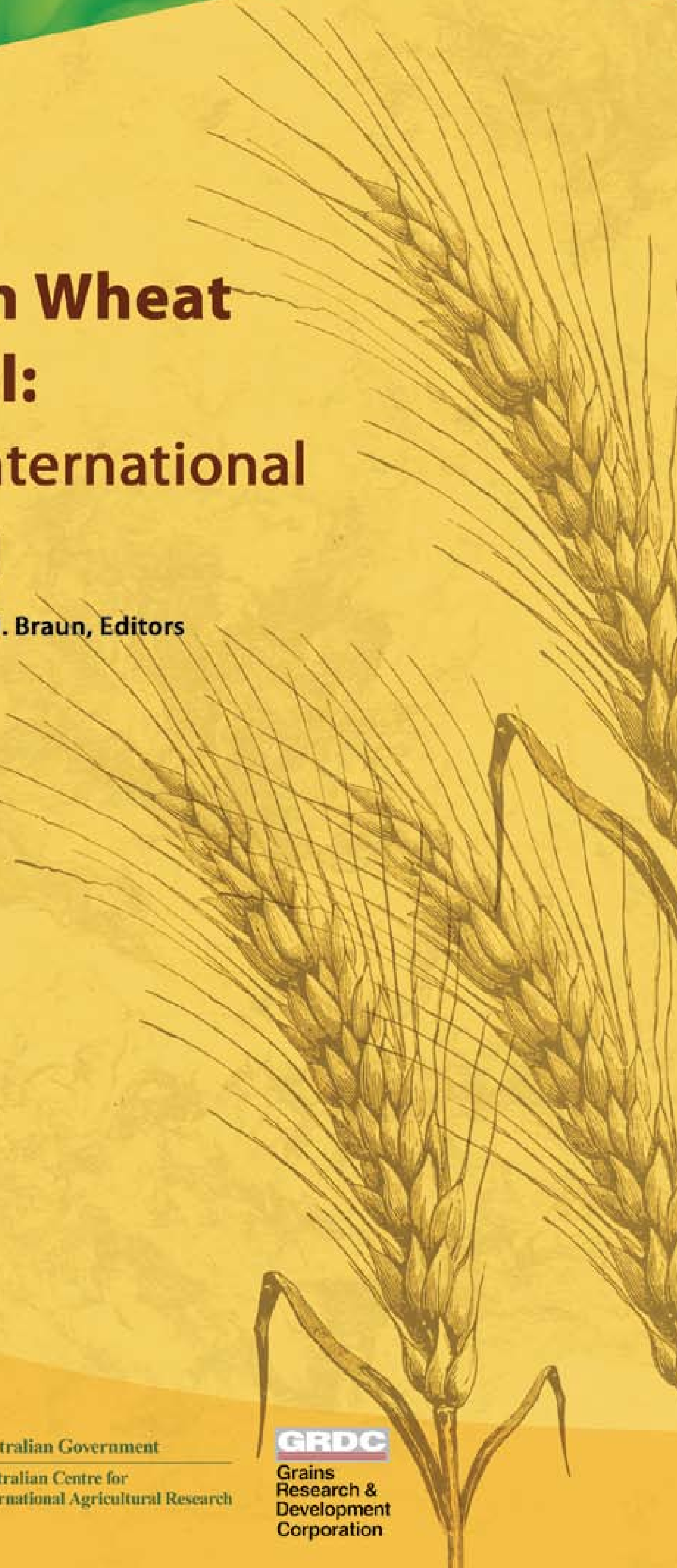
International Symposium on Wheat Yield Potential:
Challenges to International Wheat Breeding

M.P. Reynolds, J. Pietragalla and H.-J. Braun, Editors



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Foreword

Like many other patterns, investment in research is often cyclical. International centers like CIMMYT have focused substantial resources on biotic and abiotic stresses for about two decades now, but raising total productivity is also back on the development agenda. There are a number of reasons for this, among them sharp rises in the price of staple foods as well as the manifestation of detrimental effects of climate change on productivity. Those factors threaten not only the livelihoods of resource-poor people but food security at a broader level, as highlighted by the World Bank's recent World Development Report. CIMMYT has an unsurpassed record when it comes to raising crop yields from the days of the Green Revolution; as can be seen from the comprehensive scope of this new publication, our Global Wheat Program is back in the game. The book consists of proceedings of a week-long consultation of experts and leaders held in 2006 and representing all major wheat producing countries worldwide. It encompasses their ideas on how, through internationally coordinated collaborative research, proven technologies of the past can be married with new tools and approaches to meet demand for the world's number one staple crop: wheat.

Masa Iwanaga
Director General
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International Wheat Improvement: Highlights from an Expert Symposium

M.P. Reynolds, P. Hobbs, R. Ortiz , J. Pietragalla, and
H.-J. Braun

Introduction

Wheat is grown on 217 million hectares throughout the world, which produced approximately 620 million tons of grain annually during the period 2004-2006 (FAO, 2007) and provided, on average, one-fifth of the total calorific input of the world's population (FAO, 2003). In regions such as North Africa, Turkey, and Central Asia, wheat provides half of total dietary calories, for example, 1500 kcal per capita per day in Iran. Of the cultivated wheat area, half is located in less developed countries where there have been steady increases in productivity since the green revolution, associated with genetic improvements in yield potential, resistance to diseases, adaptation to abiotic stresses, and better agronomic practices (Reynolds and Borlaug, 2006a and b). Nonetheless, challenges to wheat production are still considerable, especially in the developing world, not only because of increased demand but also because of the increased scarcity of water resources (Shiklomanov and Rodda, 2003) ever more unpredictable climates (Fischer et al., 2002), increased urbanization and loss of good quality land away from agriculture (Hobbs, on CD, JAS), and decreased public sector investment in agriculture and rural affairs (Falcon and Naylor, 2005). To meet demand in a sustainable way, more resources are required to breed a new generation of genetically improved cultivars as well as implement resource conserving agronomic management practices.

A symposium was organized by the International Maize and Wheat Improvement Center's Global Wheat Program, with support from the Australian Centre for International Agricultural Research (ACIAR), in Ciudad Obregon, northwestern Mexico, in March 2006. The aim of this symposium was to bring together wheat researchers worldwide to present and discuss their ideas on how to address some of the pressing issues of increasing wheat production in a sustainable manner. Participants included 160 scientists from over 30 wheat producing countries. Many of the ideas presented at the symposium have already been published in 2007 (and are faithfully reproduced in this volume) in special issues of *Euphytica* (volume 157: 3) and *Journal of Agricultural Science, Cambridge* (volume 145: 1-3). Highlights of these papers, along with a number of oral papers published for the first time in this book, are summarized below. In addition, this volume documents the following symposium and pre-symposium activities:

(i) Reports of a one day workshop entitled "Stakeholder priorities for internationally-coordinated wheat research" involving representatives of major wheat producing countries on all continents whose remit was to develop: (a) a list of priorities for future wheat research that could best be tackled in a globally-coordinated fashion, and (b) outlines of activities that would serve as templates for future project development for selected priorities (**Reynolds et al. A**).

(ii) The summary of field day presentations given by groups of collaborating scientists in attendance illustrating the continuum between national, regional, and international-center-based research activities (**Reynolds**).

(iii) Reports of a pre-symposium survey soliciting statistics on wheat production and constraints to productivity and research from 19 countries in Latin America, Sub-Saharan Africa; Central and West Asia and North Africa; and South and Southeast Asia (see Country Surveys). Collectively these countries represent over 100 million ha of wheat and around 90% of the wheat production in developing countries (FAO, 2006). These data were also used to prepare a general summary of the constraints to productivity and research across all of the above mentioned regions (Kosina et al., on CD, *Euphytica*).

Summary of the Plenary Presentation

The symposium was opened with an address by Nobel Laureate Dr. **Norman Borlaug** (on CD, *Euphytica*) entitled "Sixty-two years of fighting hunger: Personal recollections." Dr. Borlaug described the evolution of international wheat breeding including how shuttle breeding was adopted in Mexico, enabling photoperiod sensitivity to be overcome, a pivotal step in creating internationally adapted germplasm. His talk touched on a number of historical yet topical issues, including how the 15b stem rust epidemic in the US in the 1950s is being mirrored 50 years later by the virulent new race Ug99 from East Africa; the evolution of internationally coordinated public goods research in agriculture, which led to the formation of the CGIAR (Consultative Group of International Agricultural Research), a system which despite its humanitarian mandate and many successes suffers from declining investment that is eroding the promise of food security for many of the world's most resource-poor people. He specifically addressed *high yield agriculture and the environment*, *agro-*

forestry, *drought tolerance*, *the promise of biotechnology*, *bureaucracies, and fear of change*, and finished with a quote from 1949 Nobel Peace Prize winner Lord John Boyd Orr, "World peace will not be built on empty stomachs."

Latest Technologies

Sorrels (on CD, *Euphytica*) reviewed impacts of new technologies in his article "Application of new knowledge, technologies, and strategies to wheat improvement." He highlights the complexity of the genomes of graminaceous crops and the fact that they are rapidly evolving and heterogeneous, even within species. Not surprisingly, the use of marker-assisted selection for improving complex traits remains one of the challenges facing wheat breeders. Progress in recent years includes new transformation protocols, statistical methods, methods for characterizing environments, and equipment for phenotyping traits. Sorrels also mentions progress in the area of molecular markers and microarray applications, gene silencing protocols, DNA sequencing, and transgenic crops. Comparative mapping and QTL studies have provided information about the location, identity, and number of genes controlling some economically important traits.

The articles by **William et al.** and **Ogbonnaya et al**. (on CD, *Euphytica*) review advances at the frontiers of wheat improvement research, namely, the use of molecular breeding tools and wild species for re-synthesizing wheat. William et al. argue that markers are now being used to better characterize parental lines, improve the effectiveness of crossing strategies, and track genes in segregating progenies. Although still costly, marker-assisted selection (MAS) appears to be routinely used for a few traits by wheat breeding programs worldwide. The genetic potential of re-synthesized hexaploid germplasm (when crossed to elite cultivars) was investigated by Ogbonnaya et al. They found that such synthetic-derived lines yielded 8-30% higher than the best local check in multi-site trials across diverse regions of Australia. Their results reinforce previous research conducted at CIMMYT that found that lines derived from synthetic wheat have the potential to significantly improve grain yield across environments. **Kishii et al.** (p. 120, these proceedings) reiterate the idea that a great number of useful genes in ancestral wheat species could be transferred into wheat, based on previous CIMMYT efforts using wild relatives, including *Ae. tauschii*, *T. monococcum*, *T. dicoccoides*, and *T. timopheevi*. However, **Brennan and Martin**'s article "Returns to investment in new breeding technologies" (on CD, *Euphytica*) advocates that breeding programs should carefully assess the likely economic returns from the value of incorporating new approaches into their programs, a decision that is likely to be based on the scale of the breeding operation, with low cost investments being more universally accessible.

Value of Internationally Coordinated Breeding Efforts

The paper presented by **Rajaram and Braun** (p. 103, these proceedings) reviewed efforts conducted over the last 50 years to increase yield potential gains while improving adaptation to biotic and abiotic stresses. While percent gains have been similar in irrigated and rainfed areas in absolute figures, productivity has increased considerably more in irrigated areas. Rajaram and Braun underscored the need to develop new germplasm with adaptation to abiotic stresses without sacrificing yield potential, so that farmers benefit in favorable years. A good example is Attila, a line that has been reselected or released in countries with highly contrasting environments. They also emphasized the importance of introducing new genetic diversity. For example, results from Wheat International Nurseries distributed by CIMMYT have shown that cultivars with 1B/1R are better adapted to lower input conditions, and other translocations such as 1A/1R, 7DL/7AG have already shown beneficial effects on yield potential in a range of genetic backgrounds.

To meet future demands for wheat, all available technologies must achieve an annual yield increase of about 2% until 2020. **Singh et al.** in their article "High yielding spring bread wheat germplasm for global irrigated and rainfed production systems" (on CD, *Euphytica*) report that grain yields of the best new entries were 10% higher than the local checks in international yield trials. While not all genotypes respond as well across sites, analysis of genotype × environment interaction provides opportunities to select for stable genotypes. As outlined by **Ortiz et al. (**on CD, JAS), international wheat improvement at CIMMYT has included shuttle breeding at two contrasting locations in Mexico to facilitate selection of genotypes with wide adaptation and durable resistance to rust and *Septoria*, while incorporating as wide a range of genetic diversity as possible into the thousand or so new entries that are distributed in international nurseries annually. Their article points out that CIMMYT's primary generic target product has been "genetically enhanced seed-embedded technology" which considers both strategic germplasm enhancement and adaptive breeding to mega-environments. It discusses whether CIMMYT and similar CGIAR centers will in the future invest more resources in strategic germplasm enhancement, while adaptive breeding would be conducted progressively more by national agricultural research systems (NARSs). (Strategic germplasm enhancement would include identification and utilization of novel genetic variation, e.g. from landraces and wild species—including production of re-synthesized wheat.) Given the mission of IARCs within the international development assistance community, if their products are to change significantly, they must consider the needs and relative strength of NARSs on a case by case basis.

The article by **Trethowan and Crossa** (on CD, *Euphytica*) analyzed 40 years of international spring bread wheat trials. The analysis confirmed the relevance of shuttle breeding between two locations in Mexico for global wheat improvement, since selection environments generated in Mexico associate well with global target areas. They describe how integrating information from international sites with that obtained in Mexico helps to improve the efficiency of CIMMYT's global wheat breeding effort. For more than 40 years, cooperating breeders from many countries have grown these trials, provided their elite germplasm, and returned data to CIMMYT, which has made the compiled results available to all cooperators. **Ammar et al.** (p. 108, these proceedings) also highlighted the successes of the international durum wheat yield trial over the last 22 years, based both on the shuttle-breeding approach and the global network of NARS cooperators for information feedback. Without this unprecedented global cooperation, none of the impacts (for example, in improving yield under favorable and marginal environments and enhancing disease resistance) would have been possible.

The articles by **Chapman et al.** and **Ortiz-Ferrara et al.** (on CD, *Euphytica*) assess the advantages of using a global approach by incorporating key genes (e.g., for plant height) in wheat breeding lines and emphasizing regional efforts through participatory research and client-oriented plant breeding, respectively. In the article "Relationships between height and yield in near-isogenic spring wheats that contrast for major reduced height genes" Chapman and co-authors showed how the environment influenced the phenotypic effects of two major dwarfing genes (*Rht1* and *Rht2*). Their results confirm the advantage of incorporating such genes in wheat cultivars, since there was a *ca.* 10% yield gain for lines possessing such genes, which was more evident in trials where the mean height of semidwarf isolines exceeded about 80 cm. Genotype-by-environment interaction, especially of the cross-over type, was identified by participants at the symposium as a major concern, impeding improvement especially of quantitative traits. **Eagles et al.** (p. 103, these proceedings) suggested that molecular and statistical technologies can be used to assist breeding for polygenic traits such as yield. Large data sets of the type generated by plant breeding programs are necessary, along with a large-scale genotyping of national and international entries via available markers.

Ortiz-Ferrara et al., in their article "Partnering with farmers to accelerate adoption of new technologies in South Asia to improve wheat productivity," describe how several farmer-preferred technologies have been identified for adverse conditions in eastern India and Nepal. Due to this participatory-research approach, grain harvests by resource-poor farmers significantly increased (15-70%) in locations where farmers, scientists, extension specialists, non-governmental organizations, and the private sector engaged in participatory varietal selection, thereby extending the potential impact of international public goods germplasm. Advances in wheat improvement must also consider wheat's final end-uses. Negative correlations between grain yield, grain protein concentration, and final end-use are described by **De Pauw and his colleagues** in the article "Shifting undesirable correlations" (on CD, *Euphytica*). They concluded that the undesirable correlations of grain yield, grain protein concentration, and time to maturity can be shifted by developing plants, which efficiently produce and partition carbohydrates to grain yield and have improved nitrogen- and water-use efficiency. Improvements in these traits could also be transferred to wheat cultivars in water- and nitrogen-deficient areas. They showed that simultaneous selection for quantitative and quality traits with the inclusion of marker-assisted selection, can shift these undesirable correlations. Echoing previous statements on the value of wild species, **Peña** (p. 172, these proceedings) remarks that introducing protein-enhancing genes from *Triticum dicoccoides* is a strategy to increase grain protein content while simultaneously tackling the inherent problem of improving both grain yield and grain quality.

Addressing a subject worthy of a symposium in its own right, **Duveiller and coauthors** (on CD, *Euphytica*) present strategies aimed at minimizing or controlling yield losses from major diseases and pests relevant to intensive irrigated wheat systems in the developing world. Options suggested include integrated crop management practices; breeding for genetic resistance; rotations; minimizing physiological stresses and consequent susceptibility by timely sowing and adequate use of fertilizers; and fungicide application. In their article "The challenges of maintaining wheat productivity: pests, diseases, and potential epidemics," they also advise about the risk of changes in disease spectra as a result of climate changes and demonstrate the complex relationships among crop physiology, disease resistance, and yield.

Regional Challenges

Several papers addressed wheat improvement in major grain baskets around the world: **Joshi and co-workers** (on CD, *Euphytica*) point out that India "faces a critical challenge in maintaining food security in the face of its growing population." Indian wheat breeders should therefore aim to improve the crop to address heat stress (exacerbated by global warming due to climate change); water scarcity due dwindling water supplies for irrigation; the growing threat of new virulence in diseases such as wheat rusts and leaf blight; continuous adoption of zero-till and other resource conservation technologies, particularly in the intensive and highly productive rice-wheat systems; and a high demand for better quality wheat. Challenges to wheat production in South Asia in terms of biotic and abiotic stresses are also described by **Chatrath et al** (on

CD, *Euphytica*). They point to stagnating wheat yields and the declining productivity of wheat-rice systems due to intensive tillage and burning of residues, which lead to the depletion of soil organic carbon. Excessive nutrient mining, imbalanced fertilization and over-exploitation of water resources are the other factors responsible for declining productivity. Addition of organic matter to soil through green manuring and crop residue recycling, balanced fertilization, integrated nutrient management, and crop diversification is suggested to improve total productivity in the region (see also **Gupta and Sayre** [on CD, JAS] for their analysis of the benefits of conservation agriculture in the region).

Identification of wheat genotypes with high and stable grain yield is of particular relevance for poor farmers. **Sharma et al.** (on CD, *Euphytica*) report results for the Eastern Gangetic Plains Yield Trials, grown in India, Nepal, and Bangladesh from 1999 to 2005. Lines with improved yield stability and disease resistance were identified and released, which underlines the importance and relevance of regional wheat breeding programs. Similarly, **Zhou et al.** (on CD, *Euphytica*) evaluated genetic gains for grain yield in two regions of the Southern China Winter Wheat area, using leading cultivars released from 1949 to 2000. Results showed average annual genetic gain of about 0.31% and 0.74%, respectively. In region 1, yield components did not change, though plant height was reduced; in region 2 genetic improvement of grain yield was attributed to increased thousand-kernel weight (0.65%, $P<0.01$) and kernel weight/spike (0.87%, $P<0.01$). The future challenge of wheat breeding in this region is to continue improving grain yield and disease resistance, and to develop cultivars suitable for wheat/rice double cropping under reduced tillage.

Morgounov and Trethowan (p. 162, these proceedings) reviewed recent work in the short-season, high-latitude areas of Northern Kazakhstan and Siberia, where yield potential is limited by lack of moisture in the dry years and by leaf rust in years with sufficient precipitation. They focused on three main approaches that would be required to maximize yield in the region: improved agronomic practices, better adapted germplasm, and policy interventions, especially for the former. They conclude that application of zero and minimal tillage would provide a sustainable alternative to avoid the erosion caused by current management practices. In a similar vein, **Scheeren et al.** (p. 168, these proceedings) explain the main challenges to wheat production in Brazil, highlighting the importance of agronomic practices, improved varieties, and management policies in order to increase yield potential. Pardey et al. (2006) remarked that some developing countries are becoming more self-reliant and are creating their own research and development programs; however, the more disadvantaged countries will struggle to maintain productivity growth in the face of declining spillovers.

To gain an overview of the constraints that breeders are facing, a survey was conducted covering 19 countries, representing 90% of all wheat grown and produced in less developed countries (**Kosina et al.**, on CD, *Euphytica*). The most significant constraints to wheat production were reported to be heat and water stress, weeds, and diseases. Access to mechanization and credit availability were the socioeconomic constraints most often highlighted. Lack of resources for field station operations is an important infrastructural constraint. The most desired outputs from partnerships with international agricultural centers include germplasm development and exchange, assistance in capacity building, and knowledge sharing.

Progress in Understanding the Physiological Basis of Yield

Two papers (**Fischer; Foulkes et al**., on CD, JAS) review recent work on the physiological basis of genetic increases in wheat yield potential, with the latter focusing more on winter wheat. Data from the last 10 years in northwestern Mexico indicate that yield potential progress in CIMMYT spring wheat has slowed to around 0.50% per year although physiological understanding has advanced. New research reinforces the importance of spike dry weight (g/m^2) at anthesis in yield determination, and lengthening the spike growth period through manipulation of photoperiod sensitivity looks promising, a subject which is addressed in more depth in the paper by **Miralles and Slafer** (on CD, JAS). Despite producing more kernels/m^2, the latest wheat cultivars still appear to be largely sink-limited during grain filling, while evidence from wheat and other cereals indicates the importance of increased photosynthetic activity before and during flowering to achieve increases in yield potential (see also **Reynolds et al.,** p. 136, these proceedings). Fischer highlights the need to better define and utilize traits that confer lodging resistance. He also refers to recent advances in techniques for elucidating the physiological basis of genotype × year interactions. This is specifically addressed in the paper by **Vargas et al.** (on CD, JAS). Path analysis for genotype × environment interactions using structural equation modelling enables a number of response variables to be modelled simultaneously while partitioning significance to interaction with specific weather parameters during the growth cycle.

Foulkes et al. point to the increasing number of reports of yield progress that is associated with biomass (in contrast to previous associations with partitioning alone). In winter wheat, recent biomass progress was related to pre-anthesis radiation-use efficiency (RUE) and water-soluble carbohydrate (WSC) content of stems at anthesis. They also highlight the value of introductions of alien genes into wheat germplasm (e.g., the 1BL.1RS wheat-rye translocation and the 7DL.7Ag wheat-*Agropyron elongatum* translocation). Foulkes et al. provide a list of traits that their analysis has identified as high potential candidates to raise winter wheat yield potential in northwestern Europe, including: optimized rooting traits, an extended stem-elongation phase, greater RUE, greater stem WSC storage, and optimized ear morphology.

Miralles and Slafer and Reynolds et al. consider the issue of sink and source limitations in some detail. The former sketch out evidence, a considerable amount of which has been produced by Argentinean scientists, that further increases in grain number/m^2 may be achieved through fine-tuning pre-anthesis developmental patterns to increase duration of the rapid spike growth period (RSGP) without altering flowering time. They report that there is genotypic variation in the relative duration of phenophases prior to anthesis and that theoretically photoperiod sensitivity could be manipulated to slow down and, therefore, prolong the floret primordial stage to achieve more fertile florets. However, genetic understanding is limited, and QTL analysis is indicated to identify genetic markers for which they and their colleagues have already provided a substantial background of phenotypic data. The study by Reynolds et al. looks at both source and sink (SS) limitation in populations of random sister lines to establish a more definitive link of SS traits with productivity. The SS traits formed three main groups relating to (1) phenological pattern of the crop, (2) assimilation capacity up until shortly after anthesis, and (3) partitioning of assimilates to reproductive structures shortly after anthesis. The largest genetic gain in performance traits was associated with the second group; however, traits from the other groups were also identified as being genetically linked to improvement in yield and biomass. Principal component analysis indicated potential for additive genes if complementary physiological traits are combined through breeding.

Parry et al. (on CD, JAS) considered the issue of increasing assimilation capacity at the cellular level through overcoming the limitations of Rubisco. Low activity and the competing reactions catalyzed by Rubisco are major limitations to photosynthetic carbon assimilation in C_3 plants, and they present the latest evidence that these could be most effectively addressed by introducing Rubisco with a higher catalytic rate and/or a greater capacity to discriminate between gaseous substrates. Although enzymes with desirable traits have been identified, the technology is not available to incorporate them into crop species. Parry et al. also suggest another approach via increasing the concentrations of substrates, CO_2, and Ribulose biphosphate (RuBP) at the active site of Rubisco, much as in C4 plants.

Another issue addressed at the symposium was the use of physiological selection criteria for high yield environments. **Condon et al.** (**2007,** p. 126, these proceedings) summarized the results of a project aimed to evaluate the use of physiological traits related to stomatal aperture, such as canopy temperature, leaf conductance, and carbon isotope discrimination, in early generations of the CIMMYT wheat breeding program, to break barriers to bread wheat yield potential. The results indicated considerable potential in the use of those tools to complement breeders' visual selection for high yield potential lines. Similar results are reported by **van Ginkel et al. (**p. 134, these proceedings), who focused on the use of canopy temperature depression during the selection of segregating generations to positively skew gene frequency for yield and adaptation. Their study made it evident that the combination of canopy temperature depression with visual selection improves the rate of genetic progress and was the approach that identified lines with the highest yield potential. Parallel studies have shown that a number of spectral reflectance indices also have considerable potential in selecting for yield (Babar et al., 2006a) and biomass (Babar et al., 2006b) in random inbred lines and advanced breeding lines. However, one of the aims of applying a physiological or, for that matter, a molecular marker in breeding is to increase the efficiency of selection by reducing costs or increasing turnover. One of the papers presented an economic assessment of the use of physiological selection for stomatal aperture-related traits in CIMMYT's wheat breeding program (**Brennan et al.,** on CD, JAS) The analysis lent strong support to their potential value for reducing costs, for example, by discarding physiologically substandard lines prior to extensive yield testing.

Agronomic and Environmental Strategies for Raising and Sustaining Productivity

While CIMMYT and other research groups within the CGIAR have made major contributions to agricultural development, experts in geographical information systems (GIS) postulated that the continued ability to make far-reaching contributions can only be achieved by an increased ability to collect, analyze, and assimilate large amounts of spatially oriented agronomic and climatic data (**Hodson and White,** on CD, JAS). They state that understanding the geographic context of wheat production is crucial for priority setting, promoting collaboration, and targeting germplasm or management practices to specific environments. They describe how modern GIS techniques can be used to help predict the effects of climate change and classify production environments by combining biophysical and socioeconomic criteria. Regional-scale modelling of dynamic processes such as disease progression or crop water status provide, in combination with socioeconomic forecasting, a set of predictive tools that can be applied in determining priorities for genetic improvement. They are equally applicable for developing long-term cropping systems strategies aimed at maximizing the productivity of agro-ecosystems through the application of appropriate conservation agricultural practices that incorporate local microeconomic factors (**Dixon et al., 2007,** p. 176, these proceedings).

Conservation agriculture (CA) is a resource conserving agronomic management practice that combines minimal soil disturbance (no-till) and permanent soil cover (mulch) with rotations. **Hobbs** (on CD, JAS) describes the practice and why it is important for future food production. It is an improvement on conservation tillage which is best described as an intermediate step from normal tillage agriculture and CA where minimal tillage is combined with mulch to reduce wind and water erosion and increase water infiltration into the soil. The paper goes on the describe the physical, biological, and chemical benefits of CA, which is now practiced (no-till acreage) on almost 100 million ha in the world, especially in the South American countries of Brazil and Argentina. Additional benefits are economic (less cost and yields at least equal to those of traditional farming) and social (less time). The paper also explains the importance of developing suitable equipment to enable farmers to adopt this green technology. **Ransom et al.** (on CD,JAS) describe a similar no-till, crop rotation system for dryer regions of North Dakota that results in significant yield increases and protects the productivity of the soil. They did not find similar results for the wetter areas of North Dakota but did show the benefits of fungicide application for scab control. They conclude that identifying or developing crop management practices that exploit positive genotype × management interactions is needed.

Conservation agriculture is also becoming popular in South Asia in the rice-wheat systems of the Indo-Gangetic Plains (IGP). **Gupta and Sayre** (on CD, JAS) use this case study as an example of improved resource conservation technologies (RCTs) that have led to improved profits and yields, and have impacted various environmental factors when zero-till was applied to wheat following rice harvest. Farmers were encouraged by the results, and in 2005-2006 season nearly 3 million hectares of wheat were planted this way. The paper describes various RCTs that have been introduced in the past 10 years, including laser levelling, crop diversification, and even promising results with no-till and direct seeded rice; the latter is important for 'double' no-till systems and better soil physical and biological properties.

Raised bed planting technologies are a further improvement on CA on the flat. **Sayre et al.** (p. 148, these proceedings) use data collected in the Yaqui Valley in northwestern Mexico as a case study of the findings of this technology in an irrigated wheat-maize system in a long-term trial (15 years). Farmers in the Yaqui Valley have mostly shifted to planting irrigated wheat (and most other crops) on beds rather than on the flat (with basin irrigation), but still use conventional tillage. Bed planting was adopted because of the 30-40% savings in water use. Sayre et al. present convincing data to show that it is feasible for permanent, raised beds and conservation agriculture technologies to provide opportunities to dramatically reduce tillage, save water and costs, manage retained residues on the soil surface, and diversify crop rotations resulting in the same physical, biological, and chemical benefits outlined in the Hobbs paper.

Reduced fertilizer use efficiency can result in unnecessary costs to farmers but also negative effects on the environment (pollution of groundwater). With a likely increase (largely due to rising fossil fuel prices) in nitrogen fertilizer costs to farmers anticipated in the next few years, increased nitrogen use efficiency (NUE) is needed for future food production. Two papers, **Ortiz-Monasterio and Raun** and **Girma et al.** (on CD, JAS), look at ways to improve NUE in wheat. The Ortiz-Monasterio and Raun paper is based on data collected from the Yaqui Valley in northwestern Mexico, where nitrogen-use efficiency has been estimated to be only 0.31. They evaluated the use of N-rich strips together with the GreenSeeker™ sensor and a crop algorithm as a tool to improve NUE in spring wheat against conventional farmer use of nitrogen. The results showed, on average, that farmers could save 69 kg N/ha without a yield penalty; this represents a saving of US$ 62/ha. On fields larger than 10 ha, farmers could improve farm income by US$ 50/ha just using the GreenSeeker™ sensor technology. Girma et al. used the same GreenSeeker™ normalized difference vegetation index (NVDI) sensor, calibration stamp (CS), N-rich strips, and ramped calibration strips (RCS) to improve top-dress nitrogen efficiency in winter wheat in Oklahoma, USA. They obtained similar benefits and conclude that the simplicity of these technologies means they can be readily applied by farmers in developed and developing countries. The RCS method is designed to include more pre-plant N and is more efficient at predicting top-dress N needs.

The adoption of new technologies by farmers is a prerequisite for achieving the potential of improved germplasm and crop management and improving livelihoods and environmental benefits that would contribute substantially to the UN's Millenium Development Goals (MDG). **Dixon et al.** (**2007,** on CD, JAS) draw on a wide spectrum of recent literature for understanding the pathways and processes for adoption of improved technology and the measurement of impact. The paper looks at input value chains, farm household characteristics, and an output value chain that can be visualized as a U-impact pathway to determine the rate and extent of adoption of improved varieties and practices, the magnitude of impacts, and the potential for feedback loops leading to improved functioning of agricultural innovation systems and input-output chains. The U-impact pathway proposed in the paper provides a framework to identify a set of beneficiaries that extends beyond producers and consumers, and that can be mapped using participatory methods to identify sources of the wider benefits of technology. The results suggest that the benefits accruing to agricultural research may be greater and more widely distributed across the economy than previously recognized, and strengthen the case for increased investment in agricultural science.

Concluding Remarks

The symposium simultaneously highlighted reasons to be optimistic about improving the impact of wheat breeding through adoption of new technologies, while underscoring the considerable challenges faced by agricultural researchers due increased demand for wheat as well as environmental and economic constraints. The slow though steady rate of yield potential increase in wheat is insufficient to meet predicted global demand. In the last two decades, however, research has made significant progress in a number of areas, which, if brought to a common platform, have the potential to achieve substantial increases in productivity at the farm level. These fields include (1) improved understanding of the physiological basis of yield in wheat, (2) genetic tools that would permit markers for traits associated with improved yield to be rapidly developed, (3) a new generation of statistical tools which permit genotype × environment interaction to be dissected into its genetic and physiological components, and (4) a rapidly increasing body of practical knowledge on how to implement conservation agriculture practices that would both raise and stabilize the environmental threshold on which genetic yield potential is expressed. An international center such as CIMMYT, with its expertise in germplasm development, phenotyping, strategic agronomy, use of statistical models, and practical application of molecular markers in breeding, in addition to its well developed network of scientists in national programs and advanced research laboratories around the world, is strategically positioned to provide a focal point for these disciplines.

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Stakeholders' Priorities for Internationally-Coordinated Wheat Research

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A wheat research priority-setting workshop was held with representatives of 19 major wheat producing countries from Sub-Saharan Africa (**Ethiopia**, **Sudan,** and **Zimbabwe**); South and Southeast Asia (**Bangladesh**, **China, Nepal**, **India, and Pakistan***); Central and West Asia and Northern Africa (**Azerbaijan**, **Egypt, Iran,*** **Kazakhstan**, **Morocco Tajikistan, Uzbekistan**, **and Turkey**); and Latin America (**Argentina**, **Brazil**, and **Mexico**). [1] Collectively these countries harvest 102 million hectares of wheat (47% of the global wheat area or 89% of the wheat area in developing countries) and 285 million tons of wheat production (45% of the global wheat production or 92% of wheat production in developing countries (FAO 2006). The remit of workshop participants (who, in addition to the 19 country representatives, included wheat scientists from Australia, Canada, Czech Republic, France, Italy, Japan, Spain, Sweden, United Kingdom, and United States of America, as well as CIMMYT and ICARDA; see the list of participants) was to develop:

i) a list of priorities for future wheat research that could be best tackled in a globally-coordinated fashion; and
ii) outlines of activities that would serve as templates for future project development for selected priorities.

The need for a focus on priorities was brought into sharp relief by the evidence of declining investment in international agricultural research (Pardey, these proceedings). The research areas suggested were grouped under the following sub-headings:

I. Trait and Germplasm Development
II. Crop Management
III. Genotype-by-Environment Interaction
IV. Biotic Factors
V. New Science
VI. Quality
VII. Policy/Socioeconomic Issues
VIII. Capacity and Information

I. Trait and Germplasm Development

Many of the ideas presented highlighted the perceived value of exploiting genetic diversity through wide crossing as well as exploring the physiological potential of diverse sources of germplasm, especially with regards to stress adaptation but also to increasing yield potential; specific suggestions included:

- Broader introgression of genetic diversity introduced through backcrossing with synthetic hexaploid wheat developed by inter-specific hybridization of AB and D genomes; this approach is favored as it has already provided significant impacts (Ogbonnaya et al., these proceedings).
- Raising the genetic yield potential of wheat using synthetic derived germplasm.
- Making better use of translocation lines; to date only 1B/1R, 1A.1R, and 7DL.7Ag translocations have been used systematically in breeding, but their benefits are well documented (see Foulkes et al., these proceedings). Many more translocation lines have been produced, but few have been exploited by breeders since many translocations are in a Chinese Spring background (poor agronomic type) and/or have significant negative genetic linkage drag.
- Genetic vulnerability: better exploitation of existing genetic variability. Each year CIMMYT distributes over 1,000 new genetically diverse wheat genotypes targeted to broad and diverse mega-environments through its international nursery system (Ammar et al.; Trethowan

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[1] Drs John Dixon and Petr Kosina facilitated the workshop with the assistance of Drs Mathew Reynolds and Tom Payne.

* Pakistan and Iranian country representatives were not present at the workshop but their ideas were represented through information collected in the country surveys (see pages 54 & 79), also summarized by Kosina et al (these proceedings), and through regionally based CIMMYT/ICARDA staff, and they were also invited to review this document.

and Crossa, these proceedings). Identify mechanisms that can be pursued for NARS to better utilize this pool of diverse germplasm, for example, through promotion of wider testing or through farmer participation, to achieve greater diversification of cultivars in farmers' fields (Sharma et al.; Ortiz-Ferrara et al., these proceedings).

- Develop approaches for efficient allelic transfer from wide crosses. By employing relatively simple marker approaches (at least for re-synthesized wheat), the most valuable alleles or chromatic regions from the D or AB genomes can be identified to facilitate the process of transferring genes from these sources into modern hexaploid backgrounds (Kishii et al., William et al., these proceedings).
- Improve durum wheat for marginal environments.
- Increased emphasis on targeted exchange of germplasm—including segregating population at the F_4–F_6 levels—between CIMMYT and NARS in relation to priorities at the national level.

A number of physiological traits were considered to merit urgent attention, including:

- Lodging resistance in bread and durum wheat.
- Drought tolerance, including root health;
- Heat tolerance, especially in light of clear evidence for global warming. Heat tolerance was also identified as the trait with the highest priority for improvement in a survey sent to NARS scientists (Kosina et al. these proceedings)
- Explore genetic diversity for rate of grain-filling (e.g., from Chinese sources).
- Implement stomatal aperture traits (such as canopy temperature and stomatal conductance) as useful selection criteria for yield potential (Condon et al., van Ginkel et al., Brennan et al., these proceedings)
- Increasing biomass and radiation use efficiency since partitioning may be approaching its upper limit (Fischer, Foulkes et al., these proceedings).
- Understanding the physiological basis of high biomass in triticale and why its partitioning is relatively low.
- Understanding the regulating mechanism for spike fertility and grain set (for example, through embryo/kernel abortion and sterility) to develop wheat backgrounds that are less sensitive to environmental fluxes during critical spike development stages; this could open new research avenues to raise genetic yield potential (Reynolds et al., these proceedings).

Points were raised addressing research approaches, including the potential synergy of forming research consortia to tackle research issues such as those listed below:

- Our physiological knowledge might be reinforced using a comparative biology approach whereby hypotheses about adaptive traits could be tested simultaneously on different crop species. However, it was recommended that traits of established value should be the initial research focus leading to establishment of common mechanisms and, subsequently, identification of QTLs and candidate genes.
- In the same vein, it was suggested that the extent to which yield has a common genetic basis across environments with widely varying yield levels be investigated; the QTL approach is eminently well suited to addressing this issue, assuming suitable populations can be identified that are not confounded by agronomic traits.
- The suggestion that research be organized around physiological traits of known value would be complementary to the approaches mentioned above.
- It was also suggested that breeding programs should develop and integrate selection environments to further improve the resolution and heritability of trait expression.

Finally, there were questions relating to hybrid and perennial wheat:

- What have we learned from hybrid wheat in terms of returns to investment?
- Should we invest in breeding for perennial wheat, for example, in conservation agriculture (CA) systems? If so, investment in hybrid cultivars may result in the best economic return for farmers' investments.

II. Crop Management

Much of the discussion on crop management focused on strategic research in CA, which is starting to be widely recognized as a foundation for sustainable agriculture; as having multiple benefits for farmers and the environment; and as fostering sustainable economic development (see Chatrath et al.; Gupta and Sayre; Hobbs; Sayre et al., these proceedings). An important and widely supported sentiment was the recognition that if farmers are using unsustainable practices, sowing a modern variety will not solve the underlying problem—a corollary is that the full benefits of genetic improvement will not be realized without sound crop management. This highlights the need to underpin investment in genetic technologies with complementary investment in both strategic and adaptive crop management research so that investment in the former is adequately realized. This kind of research is becoming urgent because resources for genetic improvement are increasingly being diverted from yield and quality improvement to maintaining the *status quo* (in terms of productivity) due to the need to overcome problems associated with degraded soils (i.e., micro-nutrient deficiency, incidence of soil-borne diseases, low soil organic matter leading to poor water capture and increased nitrogen losses) in both intensively and extensively cropped systems.

Successful CA systems are complex, adaptive systems that involve farmers, machinery manufacturers, extension, and input and produce marketers; the approach to research should incorporate adaptive learning of stakeholders in an innovation systems framework (Dixon et al., these proceedings). A coordinated, strategic science platform interacting with adaptive research hubs in various agro-ecosystems is one effective model for such CA research. Topics that were highlighted for **strategic research** included:

- Understanding the mitigating effects of CA on global warming through modeling its impact on:
  (i) the carbon cycle and C sequestration
  (ii) the N cycle, soil microbiology, and greenhouse gas emissions
  (iii) physical fluxes at the soil surface, i.e., water, heat, and dust particles (due to rainfall, radiation, and wind) and their interaction with crop residues and soil cultivation.
- The biological control of pests and diseases in CA systems.
- The impact of CA on system level water productivity.
- Physiological and crop genome studies to identify traits and genes that maximize yield response under CA systems.
- Adaptation of CA principles to all major agro-ecosystems (including reduced-till, bed planting, paddy rice production, and cotton-wheat systems of Central/South Asia) recognizing the need to develop a coherent transition strategy that farmers can adopt without loss of income.

Other research areas in CA were highlighted, notably a set that could be considered more **adaptive**, as follows:

- How to accelerate the adoption of CA in irrigated systems.
- Local disease/pest/weed issues.
- Genotype x soil-tillage-residue interactions.
- Crop residue for mulch versus biofuel issues.

III. Genotype-by-Environment Interaction

A far reaching suggestion was that, to enhance globally coordinated wheat research, the concept of mega-environments should be re-visited in a more dynamic way, taking advantage of modern GIS capabilities (Hodson and White, these proceedings), as well as information from GxE analyses (Chapman et al., these proceedings) that did not exist 20 years ago when the MEs were conceptualized (Braun et al., 1992). It was also suggested that breeding targets should incorporate the evolution of new cropping systems such as CA. New factors expected to be associated with substantial GxE were listed:

- Increasing biomass (as opposed to increasing harvest index)
- Water scarcity
- Global warming
- Tillage systems

Other suggestions in this area included the idea of developing a common platform for data management in IWIS III (International Wheat Information Systems) at the Cereal Research Information Laboratory (CRIL) at CIMMYT; incorporating more existing information into IWIS; and using models to help structure and better understand G x E.

IV. Biotic Factors

As expected, there were many concerns about biotic stresses since problems evolve as quickly as others are solved, as highlighted by the rising threat of the stem rust race Ug99 in Eastern Africa. Collaborators highlighted the following activities in relation to biotic stresses:

- Greater networking with CIMMYT on disease screening nurseries and novel approaches to using doubled haploid technology; gene and genomic selection techniques for major disease resistance genes.
- More work on rusts including screening and testing in rust hot spots.
- The concept of durable resistance is accepted by many wheat scientists, but its implementation is limited. Outside of CIMMYT, very few wheat breeding programs have based their breeding strategy on using minor genes as the basis for rust resistance. The concept of durable resistance should be applied by more programs.
- Assurance of durable rust resistance at high yield under CA and other new RCTs.
- Assistance in identifying pathogen races.
- Research in biological control of Sunni pest, root rots, and nematodes.
- New diseases: wheat blast (*Magnaporthe grisea*), currently reported from Brazil, Paraguay, and Bolivia, can result in zero yield).

V. New Science

There was a strong sentiment that investment in biotechnology must be made with the view to greater integration into breeding, as opposed to the isolation of new labs that has often been observed in wheat programs worldwide. There was discussion on how to influence the research agenda so it will be problem-driven and not technology-driven (e.g., the development of expensive markers for easily phenotyped traits). However, others highlighted that new does not just mean biotech and emphasized the importance of CA in its potential to have large impacts in agriculture. Specific suggestions for new research included:

- Translational research: exploiting information from model crop genomes such as *Brachypodium* and rice.
- Research on genetically modified organisms (GMOs) to identify new opportunities for disease/pest control.
- Exploit the developing wheat sequence.

VI. Quality

Although quality has been a priority in wheat improvement for many decades, more specific quality characteristics that further facilitate market access and better satisfy consumer demands are becoming substantially more important. In some instances, farmer income from wheat is reduced due to inferior grain quality. The following topics with reference to end-use quality were highlighted:

- Biofortification and micro-nutrient enrichment are considered high priorities by some NARS.

- Market orientation and alternate uses (including the possibility of energy production). It was noted that increased demand could lead to decreased need for subsidies to maintain farm income.
- The effect of global climate change—increasing temperatures/heat and increasing CO_2—on quality (protein, micro-nutrients).
- High quality protein wheat was identified by some NARS as an important priority.
- Nutritional security and acceptable end-use quality. While the former is currently of crucial importance for large numbers of poor consumers mainly in rural areas, the latter is growing continuously in importance, particularly in urban areas.
- The genetic/physiological/biochemical/chemical basis of different quality attributes needs to be better understood and addressed for the different types of food products.
- Given the above priorities related to quality characteristics, economic research is required on the trends and analysis of G x E and wheat yield vs. quality in different markets.

VII. Socioeconomic and Policy Research

The following themes were identified as priorities:

- Global food security remains a concern, as the world population will increase by an extra 2.5 billion people by 2050. Furthermore, millions of new consumers emerging from poverty are likely to increase demand for wheat products. This requires an annual wheat production increase of 2%. One consequence is the need for more visibility to promote extra funding of wheat research.
- Improved projections and *ex ante* impact assessments: Where will the gains come from to meet global demand? Would higher value/quality wheat be more competitive than high yielding, lower quality wheat? It is necessary to reassess the trade-offs and relative importance between yield and quality as trade and market liberalization has moved many countries from pursuing self-sufficiency to competing in the international market.
- What are the conditions for rapid delivery of germplasm and technologies along impact pathways and of their adaptation in local innovation systems?
- A variety of networks and partnerships with NARS socio-economists would be beneficial if adequately funded,for they could take on common questions across wheat producing countries.
- The capacity of wheat seed systems to deliver quality seed to small producers varies enormously—for example, in the case of emergencies such as Ug99 rust. These systems often lie at the interface of publicly funded research and commercial input providers. Identification of best practices for fast delivery of quality new varieties to small farmers is a high priority.
- Participatory on-farm research is important to facilitate selection among new varieties and ensure adaptation of improved agronomic practices. Moreover, diversification will often be fostered by intensification. It is necessary to gain a better understanding of intensification and diversification pathways, and their interdependence.

- Economics of trying to achieve higher yields. Real cost to farmers?
- What are the profit margins at different yield levels?
- How will biofuel affect crop production in developing countries, and should biofuels be a priority for developing countries?

VIII. Capacity and Information

It was generally recognized that opportunities for applied training in plant breeding have been dramatically reduced. Shortage of field wheat breeders has been already reported from both developing and developed countries (Guimaraes et al., 2006; Morris et al., 2006; Baenziger, 2006; Kosina et al., these proceedings). This trend is worrisome, particularly for developing countries, and ways need to be found to address it. Discussed topics can be divided into three areas:

(1) ***Training courses in breeding, CA/agronomy, diseases and pests, industrial quality, and biotechnology.*** It is necessary to encourage the organization of training courses and raise donors' interest.

(2) ***Data and information management and knowledge sharing*****.** Scientific knowledge and dynamic networks are the key drivers of agricultural and rural development. There is an urgent need for intensive knowledge flow between advanced research institutions and NARS researchers. Valuable data, information, and knowledge held by advanced research institutions all around the globe are, however, often fragmented. Access to data and their interpretation through a common data-sharing platform (i.e., ICIS/CRIL) is requested by many NARS. To complement on-line access to data and information, provision of specialized publications and facilitation of visits for technology transfer has been requested from IARCs.

(3) ***Networks and collaboration*****.** To address global challenges in wheat breeding, formation of global communities (based on traits, information, phenotyping, stress physiology, etc.) have been suggested. CIMMYT and other IARCs should promote more collaboration with universities, while NARSs could strongly benefit from joint breeding programs among themselves.

Identifying Specific Research Themes in Priority Areas

The second half of the workshop involved identifying specific research themes—those considered by the group to be of most relevance in overcoming current constraints to wheat yield—within some key research areas (selected by popular vote). The outcomes of these small 'break-out' group discussions are presented below as a series of bullet points representing potential collaborative projects, followed by some of the key comments raised in plenary presentations. Where time allowed, brief concept notes were developed.

Use of physiological traits for pre-breeding and gene discovery

The following themes were identified as top research priorities:

- Exploitation of comparative biology; taking information from major species and model species; focusing on traits and genes for which there is strong evidence of impact on yield.
- Determining common bases between abiotic stresses, such as tolerance to high temperature and drought.
- Breeding for rapid grainfilling rate to improve adaptation to heat.
- Increasing biomass by bringing together research progress in the areas of radiation use efficiency, spike fertility, partitioning, phenology, and signaling.
- Increasing the robustness of grain set, i.e., avoiding kernel abortion when environmental fluxes result in unfavorable weather during spike development.
- Tailoring phenology to environments through deployment of *Ppd, Vrn,* and *earliness per se (Eps).*
- More comprehensive approach to breeding for lodging resistance.
- Physiological and genetic characterization of parental lines used in crossing.
- Deploying and integrating physiological screens for more effective early-generation selection.
- Identifying performance QTLs that may be common across environments and gene pools for use in early-generation selection.

Methodologies to help actualize thrusts

- Use conceptual models to identify best candidate traits associated with yield improvement.
- Use targeted crosses to develop mapping populations that will not generate progeny with a large range of confounding traits, while contrasting in trait(s) of interest.
- Use association genetics when suitable RILs populations are not identified and for gene discovery to identify additive gene action.
- Backcrossing to introgress more translocations into adapted backgrounds with little drag-on, e.g., 6AL, 7DL.

Questions and answers

Q: On early-generation testing, do you have anything particular in mind?

A: Traits such as canopy temperature, leaf porosity, and spectral reflectance indices are ideal as they can all be measured within the same timeframe as visual observations are made, i.e., a few seconds/plot.

Concept note: Develop Wheat with *Improved Heat Tolerance*

Research design

- Develop conceptual models of traits for 2-3 major heat sub-environments
- Assemble available genetic diversity locally (partner countries)
- Screen local wheat accessions with potential tolerance to heat and send best lines to CIMMYT for multiplication (n=50). Materials to be tested include:
    - advanced lines and cultivars
    - products of inter-specific hybridization
    - landraces
    - (wheat alien species should be included in later phase)
- Distribute international nursery to identify best parents for crossing at CIMMYT
- Develop crosses using data from all locations and complementary trait-based strategy, followed by selection in early generations to fix populations for resistance to rusts
- Distribute F4-F5 bulks to all partners for selection under local conditions
- All partners will grow F6 derived yield trials

Partners: International centers, national wheat programs, farmers where appropriate

***Capacity building*:** training and visits in breeding methodologies including physiological trait evaluation, statistics

***Policy*:** What level of genetic improvement must be reached to target wheat-based systems as opposed to alternative crops

***Budget*:** $5 million

***Timeframe*:** 5-10 years

Thrusts in strategic crop management research

To help determine priorities, a matrix was made of management options and the relevant biological disciplines, i.e., Axis-1 included management factors: crop rotations and diversification, residue management, weed control, water management, tillage, and machinery. Axis-2 covered the disciplinary areas: soil microbiology, nutrient fluxes, soil physical characteristics, and biotic and abiotic stress. Using that framework, the following areas of strategic research were identified as high priority:

- Systematically investigate the ecology of disease and pest spectra and their interactions with beneficial flora and fauna as they evolve in response to CA.
- Quantify how CA practices (related to crop rotation, residue management, and fertilizer application) may increase nitrogen use efficiency and reduce trace gas emissions.
- Establish basic principles on how crop rotations and residue and water management practices under CA optimize system level water productivity.
- Determine the environments in which CA practices can significantly ameliorate effects of a range of abiotic stresses through improving root health and the soil's buffering capacity in terms of nutrients and water availability.

- Determine threshold levels of residue retention for sustainable CA practices considering alternative uses of residues including livestock feed, biofuel, etc.
- Develop a set of broad principles for correct adaptation of conservation agriculture to avoid "horror stories" where component technologies are promoted out of context (e.g., zero till without residue retention) as "magic bullets."
- New breeding and selection strategies for CA.
- Socio-economic determinants of adoption for CA.

Questions and answers

Q: Can what has been learned under conventional agriculture be applied to CA; and do you foresee a development of generic recommendations for farmers practicing CA?

A: The most desirable approach will be to develop a number of research platforms with different partners in well defined system/environments so as to address these questions and extend the technology once such recommendations can be confirmed. The biggest knowledge gaps are in the areas of how CA affects insects and diseases (entomology and pathology). Greater opportunities for consultation with client countries would expedite the whole process.

Q: I don't see the word "long-term" or "buffering" anywhere in the thrusts.

A: We believe these concepts are implicit to CA.

Q: One of the biggest challenges I have heard to CA is in the rainfed areas where residues may not be available due to the type of system and alternative uses.

A: Better knowledge of the amount of residues to be left in the field and options for crop diversification (not just in CA) is needed.

Q: What about lodging issues?

A: CA practices *per se* should not result in increased lodging; however, lodging requires more attention.

Comment: On the question of exploiting G x M interaction, there has been great investment in conventional systems, but so far little research has been devoted to select wheat specifically adapted to CA (exploitation of G x CA).CIMMYT plans to investigate whether there is significant G x CA. CIMMYT has made a commitment to focus on CA and to promote CA technologies. Research on improving conventional systems will be the responsibility of NARS.

Concept note: *Breeding cultivars for conservation agriculture*

Research design

- Define the most broadly adopted CA practices.
- Design a conceptual model for CA adaptive traits.
- Identify lines encompassing the promising CA adaptive traits.
- Genetic improvement using complementary trait-based crossing strategy.
- Three selection environments: (1) select all generations under CA, (2) all under conventional tillage and (3) alternate CA and conventional tillage.
- F_4-F_5 will be sent to all partners.
- F_6 derived yield trials under both CA and conventional tillage systems.
- Include farmers using CA for testing of selected lines.
- Develop mapping populations for CA traits.

Partners: National wheat programs, farmers, CG centers.

Capacity building: Training and visits in CA and trait-based breeding methodology.

Policy: Ensuring residue retention, appropriate machinery, and credit.

Budget: $5 million

Timeframe: 5-10 years

Genotype x Environment Issues for the Next 20 Years

Moving from genotype x environment to gene x environment interaction

As our ability to identify genes and their function increases, it will become more feasible to conduct gene x environment analysis (e.g., Eagles, these proceedings). In the meantime, it is proposed that the following genetic entities can be used in analysis (i.e., what counts as a gene?):

- Chromosome translocation
- QTLs
- Genomic regions
- Known genes

It was recognized that the feasibility of this approach is restricted by the current understanding of the genetic basis of adaptation of cultivars as well as interactions of genes with genetic background (epistasis, pleiotropy, etc). Therefore, genetic backgrounds (i.e., genotypes as opposed to genes) will remain important to analytical approaches for understanding GxE.

Understanding the environment (E)

While GxE analyses that have been conducted with limited environmental data provide extremely valuable information (Trethowan and Crossa, Ammar et al., Chapman et al., these proceedings) understanding the underlying environmental causes of GxE will be enhanced by more sophisticated characterization of environments (Hodson and White, Vargas et al., these proceedings). To achieve this, a more systematic approach must be adopted to characterizing experimental sites as outlined below:

- Weather to be characterized more comprehensively over the whole crop cycle.

- Soils to be characterized in terms of physical, chemical, and agronomic properties.
- Inputs in terms of water, nutrients, and crop protection to be monitored.
- Additional management factors relating to cropping systems to be recorded.
- Test sites may change over years in terms of climate, agronomy, and disease spectra.
- Identification of mega-environments and micro-niches.

Developing genotypes that adapt to variable environment over time

Environmental variations at one location over years is forecast to increase with global climate change. Under such conditions, breeding cultivars with specific adaptation is not feasible, as the variation at one location over years could be greater than among locations in a given region in a given year. To develop cultivars that are robust to seasonal variation in weather at a given locality, systematic, long-term studies on GxE are needed. The following ideas were proposed:

- Identify sites that represent key environments, in partnership between national wheat programs and international centers.
- Data coming from yield trials at such sites can also help to define the relative efficiency of global versus regional nurseries for a range of strategic breeding objectives (see Ortiz et al., these proceedings).
- Shuttle breeding between appropriate sites would help in developing genetic backgrounds that are stable over a range of target environments (e.g., combining disease resistance or adaptation to several abiotic stress factors).

Concept note: *Characterization of abiotic, biotic, and management factors in hot target environments*

High temperature stress is currently affecting—and, due to climate change, will likely increasingly affect—wheat production throughout the developing world. Currently, at least 9 million ha of wheat in tropical or subtropical areas (including Bangladesh, India, Pakistan, Nepal Ethiopia, Sudan, and Egypt) experience yield losses due to heat stress (Lillemo et al., 2005). This area is likely to increase if current trends and future predictions about global warming continue (Fischer et al., 2002; Hodson and White, 2007). A recent and extensive study on the effects of climate change for India and south Asia (DEFRA, 2005) predicted marked increases in both rainfall and temperature, with temperatures projected to rise by as much as 3-4ºC by the end of the century. Research on heat stressed wheat environments is therefore a high priority. Environmental data that are generally available for G x E type analyses frequently do not include information on soil properties, soil-borne diseases, water availability, and cropping systems, but in addition to meteorological data and crop management information, these would help to dissect the factors driving G x E much more effectively. A good understanding and characterization of target environments to reduce genotype by environment (GxE) interactions and effectively target germplasm to specific environments are essential elements of any plant breeding program. Opportunities now exist, through improved availability of climatic datasets, to build upon GxE analyses conducted by CIMMYT that have elucidated key factors, which differentiate distinct wheat heat-stress environments (Lillemo et al., 2005) and add a spatial and temporal dimension to this work. In addition, availability of increasingly sophisticated climate change models offer opportunities for predictive change studies. With reliable phenotypic data and appropriate statistical techniques, variance associated with G × E can be partitioned into discrete environmental variables in time, and interpreted in terms of the unique response of a genotype, at a given phenological stage, to year to year variation in weather patterns (e.g., Crossa et al., 2004; Lillemo et al., 2005).

Research tools and approaches:

- GIS
- Modeling
- Data bases
- Climate change scenarios
- Identification of mega-environments and micro-niches
- Special international nurseries
- Advanced statistical analysis to partition GxE

Partners: National Wheat Programs, CG centers, Advanced Research Institutes.
Capacity building: Training and visits in GIS, statistics, etc.
Budget: $1.5 million
Timeframe: 3-5 years

Quality thrusts

- High priority. Collaborative research to determine and implement evaluation protocols for milling characteristics and end-use quality attributes. This research should emphasize the use of higher throughput phenotyping techniques, particularly NIR, and allow for the use of molecular markers when their use is warranted. It should be conducted based on a well defined trait profile of consumer preferences or end-user acceptance.
- High priority. Conduct research on the stability of quality attributes across environments and crop management practices, aiming to reach an acceptable compromise (when possible) between productivity and quality, especially in the context of global warming.
- Conduct research on the stability of quality traits under high temperature (heat) and sprouting-promoting environments, especially in the context of global warming.
- Adopt a research agenda that considers quality attributes for broad categories of products rather than highly specific ones:
    - Leavened breads
    - Steamed bread
    - Noodles
    - Cookies/cakes
    - Pasta/semolina

- High priority. Establish market/consumer trend projections and value chains (supply, demand) for the different wheat market classes by country or region, and study the potential impact of trade issues for more targeted policy advocacy.
- High priority. Address the increase in grain micronutrient density or biofortification and grain factors influencing micronutrient bioavailability, also in the context of increasing CO_2 concentrations leading to higher yields (which may result in decreasing MN concentrations and MN contents due to dilution; this is an effect similar to protein content generally decreasing with increasing yields). The complexity of this issue is acknowledged and will require a concerted research effort to investigate the relationship between concentration in the grain and availability in the soil, the consistency of expression across environments, the potential effect of grain processing such as milling, and actual bioavailability of micronutrients for human nutrition once packed into the grain.
- Medium/high priority. Address the potential detrimental effects of mycotoxins on human health, especially in a context of increased adoption of conservation agriculture practices and greater incidences of pathogens such as Fusarium head blight.
- Medium priority. Explore market possibilities and economic viability of alternate industrial uses (non-nutritional, non-food crop). Specific target traits will depend on the genetic variability available.
- Low priority. Health (human) food.
    - High fiber.
    - Low starch digestibility.
    - Low phytate.
    - Quality protein wheat (amino acid profiles).

Concept note: ***Characterization of physiological and grain factors influencing protein quality in hot target environments***

Heat shock proteins activated as defense mechanism against heat stress may alter the balance of gluten protein entities, negatively affecting the baking quality of wheat. A good understanding and characterization of target environments to reduce negative genotype by environment (GxE) interactions are necessary in developing germplasm showing yield and quality stability in targeted areas.

Research tools and approaches:
- Genotyping and phenotyping protein-related grain factors
- Data bases
- Climate change scenarios
- Identification of mega-environments and microniches
- Special international nurseries
- Advanced statistical analysis to partition GxE

Partners: ICs, National Wheat Programs, AIs.
Budget: $0.5 million
Timeframe: 3-5 years

Rainfed spring wheat thrusts
Objectives:
- Identify physiological traits underlying water use efficiency and heat tolerance, their genetic control, and develop tools for plant breeding.
- Identify genotypic characteristics and management practices systems that maximize performance under various environments (drought stress, heat stress, favorable conditions).

Research 1:
- Define which physiological traits and selection tools are available
- Screen parents of existing and available mapping populations (CIMMYT, partners)
- Identify gaps and develop populations if not enough variation available

Research 2:
- Determine the target set of management practices to be investigated
- Select genotypes under defined management practices to maximize return from management practices
- Study gene x management interaction

Partners:
- ICARDA
- NARS (CWANA)
- Advanced Research Institutes

Budget proposals:
- First project: $250,000/year for 5 years
- Second project: $200,000/year for 10 years

Winter, spring bread and durum wheat thrusts
Three main thrust emerged from the discussions on spring durum wheat, namely, the need to address breeding for warmer and less predictable environments in the context of global warming, the need for continued breeding for drought prone conditions, and the inclusion of conservation agriculture as an environment that can influence how breeding is conducted. For winter wheat, the consensus was that more insight into the effect of vernalization and photoperiod genes is required to better tailor wheat germplasm to respective environments, also in the context of global warming.

Whereas the session was about presenting ideas and prioritizing research focus, it was clearly underlined that national programs as well as international research centers, need to conduct internal analysis of their activities and priorities in order to determine which resources, if any, could be contributed to this new research. Since currently funded activities are providing the bases for any further research, it is likely that no currently available resources could be diverted, and that new projects would require extra funds. For these research projects to be meaningful, the different partners should be involved right from the planning phase.

Brainstorming Session

At the end of the workshop, all participants were invited to make additional comments around the table:

Regional issues

- Speaking in relation to Southern Africa, we are doing well but there are problems with the Russian wheat aphid, and heat and drought stress. Zambia is landlocked and needs *ca.* 500,000 tons of wheat. To meet this demand, yield needs to increase, and this requires increasing the productivity of wheat fields managed by resource-poor farmers.
- Genetic vulnerability: In South Asia farmers are sitting on a time bomb. Huge areas are sown to two dominant varieties, both susceptible to yellow and stem rust. What can we do to promote diversification?
- Hybrid wheat scientists in the Punjab and Haryana are looking for ways to extend the yield barrier.
- North Africa (Morocco), 40 varieties derived from CIMMYT and ICARDA germplasm, but the bulk of what is grown is of a relatively narrow spectrum. Seed of recently released varieties is not readily available. With regard to management, we are facing drought stressed conditions, are still plowing a lot, and facing land degradation issues. Need fuller implementation of zero- or reduced-till systems (CA practices). To promote these practices, there is a need for strong partnership and knowledge sharing.
- In Egypt, wheat yields are very high, but there is no further area to expand production. A huge concern is that Ug 99 may soon reach Egypt and cause major losses. CIMMYT and ICARDA have an important role to share information and publications in potential and actual disease hot spots. Training is essential for maintaining high levels of productivity.
- In Mexico, quality is a key objective, and yield *per se* is no longer the highest priority. To keep durum wheat farming profitable and bread wheat farming sustainable, CIMMYT needs to consider present and future market scenarios.
- In Ethiopia, the two dominant wheat species are bread wheat and boro wheat, concentrated in rainfed conditions, making production tenuous. Less emphasis is given to durum under marginal or unfavorable conditions. This should be changed, since durum is a traditional Ethiopian crop.
- Wheat is important for Kazakhstan. Drought tolerance and better resistance to diseases, in particular leaf rust and septoria, is key for the north. Developing Ug99 resistant varieties is important. There is a lack of trained young scientists.
- In Bangladesh and Eastern India, the severity of leaf blight (spot blotch) must be addressed soon.

Crop management

- There is a tendency to look at wheat in isolation. Breeding for systems needs to be emphasized, exploiting G x Management interaction.
- There is a global shortage of both plant breeders and agronomists, particularly for wheat.
- We are looking for genetic solutions to heat stress. Can we think of non-genetic management solutions to the heat stress dilemma?

Germplasm development

- Have we achieved the maximum level of harvest index?
- Triticale yields are at least as high as bread and durum wheat yields, but triticale biomass is considerably higher. Could we understand why and how triticale produces more biomass and apply that information to wheat to increase wheat biomass and, eventually, its yield potential?
- We have a tendency to look at a species in isolation. If I had the resources, I’d make a comparative physiology study among 10 crops using a trait-based approach that could link into genetic knowledge as it becomes available.
- A trait-based project on lodging resistance in spring bread wheat.
- Must follow-up on stomatal aperture traits for application in breeding.
- Private companies claim to have improved drought tolerance in wheat by about 20%. What is CIMMYT and the CGIAR going to do about that? Comment: There is no GMO wheat released; CIMMYT works with GMOs, and if these genes are available, CIMMYT will explore these genes and test them in wheat.
- Exploit existing variation; many translocation lines have been developed for specific traits, but they have not been tested very widely. This project, funded by GCP-Generation, is in progress.
- Perennial wheat: where do we want to be in 15-20 years?
- What new diseases might arrive and what will their impact be? How can we act proactively on this? What will we do and what can we do?
- Not enough focus on soil health that goes beyond fertility alone.

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A Worldwide Wheat Research Network: Highlights from Field Day Presentations of the International Wheat Yield Symposium

Matthew Reynolds

Field day presenters

National agricultural research systems

A Absattarova, KIZ, Kazakhstan
B Alimgazinova, MOA, Kazakhstan
Z Akparov, GRI, Azerbaijan
N Barma, WRC, Bangladesh
M Camacho, INIFAP, Mexico
A Chermiti, INRAT, Tunisia
R Dahan, INRA, Morocco
J Elias-Calles, PIAES, Mexico
P Figueroa, INIFAP, Mexico
Z He, CAAS, China & CIMMYT
J Huerta, INIFAP, Mexico
Xu Jia, CAS, China
AK Joshi, BHU, India
Süleyman Karahan, TAGEM, Turkey
Hongxiang Ma, Jiangsu Acad Ag Sci, China
H Mumudjanov, TAU, Tajikistan
C Royo, U. Llerida, Spain
R Sharma, IAAS, Nepal
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OVERVIEW

Presentations by scientists from CIMMYT and collaborating national agricultural research systems (NARS) covered breeding for yield, drought and heat adaptation, disease resistance, quality, physiological trait-based selection and conservation agriculture. The main operational principles of the wheat improvement network that CIMMYT coordinates can be represented as a wheel, where the outer rim depicts farmers, the central hub a small group of researchers focusing on problems of global importance, and the spokes the flow of germplasm and information in both directions via collaborating wheat scientists worldwide.

Many of the presentations referred to the international wheat nurseries (IWNs). Global distribution of nurseries (www.cimmyt.cgiar.org/wpgd) remains one of the central pillars of international wheat breeding, providing a dual function. The first is the distribution of new genotypes that are diverse enough for broad and specific adaptation to regional and local climates, while embodying universally desirable characteristics. The latter include genetic resistance to a broad spectrum of pathogens, high and relatively stable yield, and appropriate end use characteristics. National programs may choose from over two dozen nurseries, encompassing approximately 1,000 new genotypes each year. Since nursery sets are targeted for specific agroclimatic, mega-environments (irrigated, semi-arid, high rainfall, etc.), national program breeders request those sets most appropriate for their target environments, and select the genotypes with the required characteristics to develop locally-adapted cultivars. The other function of international nurseries involves creating a global database for each nursery, based on feedback provided by national program partners on traits such as response to local diseases and pests, seed characteristics, adaptation in terms of maturity class, and in the case of the smaller sets, agronomic yield. This feedback is part of a mechanism for ensuring that internationally coordinated breeding remains relevant to local requirements in terms of influencing the nature and composition of successive international nurseries (Trethowan and Crossa, 2007; Ammar et al., this issue).

Mexico encompasses a number of diverse agro-ecological environments, making it very suitable for achieving rapid genetic gains in spring wheat breeding of global relevance. There are also highly-focused nurseries tested in so called “hot-spots”, a good example being Ethiopia, where resistance to the highly-virulent new strain of stem rust, *Ug99*, is tested. Many NARS conduct additional screens for local adaptive traits on IWN entries including, for example, Hessian fly resistance by INRA-Morocco or enhanced resistance to *Septoria tritici* by INRAT-Tunisia. On the other hand, the international winter wheat improvement program is hosted by Turkey and run by Turkish, CIMMYT, and ICARDA scientists.

Mexico is also a location for upstream research in collaboration with NARS globally. The portfolio of projects includes research to apply molecular markers in breeding in collaboration with Australia, studies led by Spain regarding the effects of photoperiod sensitivity on the adaptation of CIMMYT germplasm at different latitudes, work to identify the genetic basis of traits associated with spike fertility in collaboration with the UK, and engineering of a new generation of fast and affordable spectral radiometers for early-generation selection in collaboration with US partners, among others.

Finally, capacity building and training were frequently mentioned as vital components for maintaining the vitality of the international wheat research network.

BREEDING

Collaborative international wheat breeding has been ongoing since the 1950s (Reynolds and Borlaug, 2006) and representatives of longstanding partners such as Mexico, India, and China talked about the many benefits of germplasm exchange. For example, shuttle breeding between China and CIMMYT seeks to improve resistance to scab, powdery mildew, and yellow rust. More than 35 institutes in China receive CIMMYT wheat international nurseries annually. CIMMYT wheat has been extensively crossed with Chinese wheat to improve yield potential, processing quality, resistance to rusts, and broad adaptation. Chinese wheat contributes several desirable traits to CIMMYT wheat, including resistance to fusarium head scab, karnal bunt, and *Septoria tritici*, as well as traits such as high yield potential and lodging resistance, fast grain filling rate, and tolerance to high temperatures. Derivatives of Chinese wheats have been sent to many countries through CIMMYT international nurseries.

Demand for better quality wheat has rapidly increased as of the late 1990s. China and CIMMYT have taken a joint action to promote wheat quality, in collaboration with Australia (BRI Australia, Department of Western Australia, CSIRO), USDA-ARS, and JIRCAS. The major activities include establishment of a standardized testing system, molecular marker development and utilization, and training. The CAAS-CIMMYT joint wheat quality laboratory, established in 1998, has become internationally recognized for promoting Chinese wheat quality. Target traits include protein content, grain hardness, milling quality, yellow pigment, PPO, dough reheology, solvent retention capacity (SRC), alkaline water retention, and pentosan. Target products include pan bread, Chinese noodle, steamed bread, and cookies, with emphasis on noodle and steamed bread.

Some 50 million hectares of wheat worldwide is affected by heat stress. Of this, about 30% is located in the Eastern Gangetic Plains of South Asia, home to nearly 1.3 billion people and where rice-wheat rotations constitute the main cropping system. Besides heat, *Helminthosporium* leaf blight (HLB) and leaf rust are important biotic stresses. CIMMYT-South Asia staff, in close collaboration with the NARS of Bangladesh, India and Nepal, initiated breeding efforts in 1997 to tackle these stresses. A new regional nursery called the “Eastern Gangetic Plains Screening Nursery (EGPSN)” was launched that year, where improved material from CIMMYT and the region has been distributed since then. The regional breeding work for these stresses is done in close collaboration with the National Wheat Research Program of Nepal, using two hotspot locations (Bhairahawa and Rampur). After nine years, good progress has been made in identifying germplasm with combined heat and HLB tolerance. Breeders in the region have used this material extensively in their crossing programs. Two varieties (BAW-1006 and BAW-1008) were released in Bangladesh out of this nursery in 2005. NARS and CIMMYT scientists have exchanged germplasm and information with scientists at CIMMYT-Mexico. Synthetic wheats developed at CIMMYT, as well as other sources of heat and HLB resistance from Brazil, China, and elsewhere, have been useful.

Examples of country-level research that feeds into the network include evaluating new sources of HLB resistance to identify novel resistance genes in Nepal, and the promotion of basic studies of yield decline as well as recent analytical approaches (stay green trait, CTD, stomatal conductance, among others) in germplasm in India and segregating generation of targeted crosses. Mapping populations are also being developed to further understanding of traits.

To facilitate rapid selection of germplasm adapted to dry areas, breeders based in Mexico have adopted marker assisted selection for root health issues including resistance/tolerance to cereal cyst nematodes, root lesion nematodes, crown rot, and boron toxicity, using markers from Australian collaborators (William et al., 2007). Lines positive for these traits are sent to the CIMMYT-Turkey program for confirmation under field conditions. Other disease-resistance genes studied this way are those for resistance to BYDV and fusarium head scab, along with minor leaf rust resistance genes. In Mexico, the entire crossing block is screened for all available markers, including those for improved milling and end-use quality parameters, major resistance genes, and dwarfing genes. In 2006, approximately 47,000 such assays were made.

Representatives of wheat farmers cooperative (PIEAES) in the state of Sonora, Mexico, were present at the field day. As well as providing all of the land for CIMMYT's main breeding station in Ciudad Obregón, Sonora, the collaboration has resulted in synergies in the development, deployment and multiplication of wheat germplasm. PIEAES is responsible for the seed multiplication and dissemination of new varieties, which has proven an effective way of insuring the best wheat germplasm becomes available to the farmers in northwest Mexico.

CONSERVATION AGRICULTURE

Long-term conservation agriculture (CA) trials have been established at three CIMMYT stations in Mexico to determine the effects of different tillage, residue management, and rotation practices. Trials serve as platforms to:

- Determine long-term effects on crop production and soil chemical, physical, and biological properties, as well as water productivity, disease, pest and weed dynamics (Govaerts et al., 2007).
- Provide opportunities for training and thesis projects.
- Support development of appropriate implements.
- Provide demonstrations for farmers.

One significant conclusion coming out of this effort is that crop management, especially CA, is not as site specific as commonly assumed. A good example is the widespread dissemination of raised bed planting from the Yaqui Valley in northwest Mexico to about 20 countries in Asia, as well as in Africa and Latin America. To facilitate this, CIMMYT wheat crop management specialists have pioneered the development of multi-crop/multi-use implements (Hobbs 2007; Sayre et al., this issue).

Whether or not genetic yield potential continues to increase, all farmers in developing countries need crop management technologies that provide immediate, major reductions in production costs, while insuring enhanced long-term sustainability by reversing soil degradation from extensive tillage and crop residue removal. The development and deployment of appropriate conservation technologies require more support, even if it means shifting resources from other, more upstream research efforts.

Another aspect of crop management research with immense strategic value was the Zn micronutrient project spearheaded by Turkey, in collaboration with CIMMYT and various universities and research institutes and with support from NATO and DANIDA. Zinc deficiency exacerbates drought stress, due to its essential role in detoxification of reactive oxygen species; the research led to recommendations for foliar applications affecting 4 million ha of wheat in Turkey alone (Bagci et al., 2007).

PHYSIOLOGY

Wheat physiology addresses four main areas: (1) physiological and genetic understanding of yield and stress adaptation (underpinning); (2) utilization of genetic resources in parent building and strategic crossing; (3) development of physiological and genetic selection markers; and (4) capacity building for visiting scientists and students in application of these approaches in breeding. A broad collaborative platform permits experimental germplasm, traits, and hypotheses to be tested in a range of appropriate target environments. A current focus is the identification of molecular markers associated with drought-adaptive traits, a project encompassing collaborators on all continents, that will complement physiological selection tools such as canopy temperature and spectral reflectance indices. Another important area is the development of conceptual models of stress-adaptive traits that are used for characterization of potential parents among genetic resources, permitting strategic crosses to accumulate complementary physiological traits in new progeny.

CAPACITY BUILDING AND INFORMATION SHARING

Capacity building is a pivotal activity for the international wheat research network coordinated by CIMMYT. It provides for information dissemination on wheat improvement approaches, both tried-and-true and cutting-edge, and furnishes a forum for scientists from different countries to meet, share experiences, and become partners. Chinese presenters provided the following statistics: over the last 10 years, CIMMYT has trained over 60 Chinese wheat scientists in breeding, cereal quality, and crop management. They have become the leading scientists in provincial programs. CIMMYT and the Chinese Academy of Agricultural Sciences (CAAS) have also jointly organized 16 workshops and training courses on breeding, quality, and disease resistance, with more than 1,500 participants. CIMMYT and Chinese scientists have published more than 50 papers in leading Chinese journals and over 20 papers in international journals. During 1997-2005, more than 20 postgraduate students did thesis work at the CAAS-CIMMYT quality lab. Ten postgraduate students are currently working on wheat quality, powdery mildew, yield potential, and molecular markers. Presenters from Turkey and South Asian countries highlighted the value and continued need for centrally-coordinated capacity building.

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Issues of Wheat Production in Argentina

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Wheat is the most important winter crop in Argentina, grown during the period 1995-2005 in 5.5 million hectares average, yielding about 2.6 tn/ha and representing an approximate production of 14 million tons per year. From them, 5.5 million tons/year are destined to local use and the rest is exported to Latin America (especially Brazil), to Africa and to Middle East. Argentina is heading towards a better system of classification of its production, to offer a wider range of specific grain features both to internal and external markets to satisfy the increasingly demanding industrial needs.

The amount and quality of Argentina wheat production are affected every year by different limiting factors, abiotic and biotic. Among the former, hydric and nutritional stress and high temperatures during anthesis are the most important. Among biotic factors, fungus diseases stand out by their incidence in humid years, being leaf rust (*Puccinia recondita*), head blight (*Fusarium graminearum*) and leaf spot (*Septoria tritici*) the most frequent diseases.

From 1990 to 2000 the economic environment favored technology: fertilization (N, P and S), watering and fungicides usage increased, accompanying the increase in cultivar availability and their potential yield, and in no-tillage management. During that period, yield increased by 49 kg/ha/yr, but from 2001 on the economic situation was less favorable to technology acquisition. As a consequence of the changes in cultural practices, the quality of the production was diminished and the incidence of certain diseases as yellow spot (*Drechslera tritici repentis*), leaf spot and head blight increased. Due to the fact that exists partial resistance to such pathogens and only a low level of tolerance is available; the control strategy is the integrated management, including the usage of resistant cultivars, fungicides and cultural practices. It is to be noticed the frequent changes in virulence of some pathogens as the leaf rust, endemic in the northern and central regions. In such cases, the development of resistant cultivars is the priority, as there is wide genetic availability to control such pathogens.

Genetic improvement is a low cost, nonpolluting technology, highly efficient to improve productivity, yield stability, and grain quality. The diversity of productive circumstances and consumer markets requires the development of genotypes adapted to diverse situations. To achieve so, it is necessary to complement traditional breeding programs with physiological bases and biotechnological tools. Among the latter, the use of molecular markers to assist selection of health and quality traits controlled by main genes, is more effective and faster than conventional breeding, allowing the immediate incorporation of those traits in well-adapted, high-yielding germplasm.

Argentina

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Table 1. Cultivars grown and released in irrigated and rainfed areas, 1955-present

(i) IRRIGATED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number/year*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	60,000	0	5.2			Baguette 10	Prointa Gaucho	
1985-1995	30,000	0	4.2					
1975-1985	20,000	0	3.4					
1965-1975								
1955-1965								

(ii) RAINFED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number/year*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	6,173,000	0	2.3		8	Klein Escorpion (15%)	Buck Guapo (15%)	300-600
1985-1995	5,084,000	0	2.0		5	Klein Cacique	Prointa Federal	
1975-1985	6,057,000	0	1.7		9	Klein Chamaco	Marcos Juarez INTA	
1965-1975	5,331,000	0	1.4	1.4		Marcos Juarez INTA	Klein Atlas	
1955-1965	4,997,000	0	1.4	1.4		Klein Rendidor	Klein Atlas	

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

(i) IRRIGATED AREAS

2 yr period	Conventional tillage *hectares sown*	Reduced/zero tillage *hectares sown*	*%*	Average N:P:K applied *kg/ha*	Fully mechanized *% of area*	Sown on flat *% of area*	Sown on raised beds *hectares sown*	Gravity:sprinkler irrigation *ratio*	Irrigation applied *mm or frequency*
2004-2005	20,000	40,000	67	100(80%N, 19%P,1%S)	100	100	0	0	200 mm
2002-2003	12,600	17,400	58	100	100	100	0	0	200 mm
2000-2001	10,000	10,000	50	100	100	100	0	0	200 mm
1998-1999					100	100	0	0	200 mm
1996-1997					100	100	0	0	200 mm

(ii) RAINFED AREAS

2 yr period	Conventional tillage *hectares sown*	Reduced/zero tillage *hectares sown*	*%*	Average N:P:K applied *kg/ha*	Fully mechanized *% of area*	Annual cropping *% of area*	Cereal-fallow *hectares sown*	Weed control (grasses) *methods*	Broadleaf weeds *methods*
2004-2005	2,762,000	3,500,000	56	50 (80%N, 19%P, 1%S)	100			Chemical - rotations	Chemical - rotations
2002-2003	3,170,000	3,000,000	49	38	100			Chemical - rotations	Chemical - rotations
2000-2001	4,302,000	2,500,000	37	30	100			Chemical - rotations	Chemical - rotations
1998-1999	3,876,000	2,000,000	34	33	100			Chemical - rotations	Chemical - rotations
1996-1997	5,142,000	1,500,000	23	32	100			Chemical - rotations	Chemical - rotations

Table 3. Current and emerging constraints to wheat production

Environmental Constraint Abiotic	YES/NO	Description of constraint	Area affected hectares or % of total area	Typical yield loss range (%)
Low rainfall	Yes	Most important towards west	80	<50
Declining water resources (for irrigation)	No			
Heat	Yes	Important in northern areas (areas I, V north, NOA, NEA)	20	<25
Cold	Yes	In no-tillage	<25	<25
Salinization	No			
Soil physical degradation	No			
Micro-element deficiency (e.g., Zn, Bo)	No			
Micro-element toxicity (e.g., Al, Bo)	No			
Lodging	Yes	When yield is higher than 6 t/ha (humid years or under watering).	15	<30
Other	No	Macronutrients deficiency in humid years.	50	>25
Biotic				
Diseases	Yes	Head blight (Fusarium graminearum), rusts (Puccinia recondita, striiformis and graminis) and foliar deseases (mainly Septoria tritici)	80% in humid years	<50
Pests	Yes	Aphids	20	<20
Weeds	Yes	Lolium multiflorum Avena fatua Polygonum aviculare	50	<25
Socioeconomic constraint				
Credit	Yes	Very expensive		
Seed availability/quality	No			
Fertilizer availability	Yes	Very expensive		
Fungicide/pesticides/herbicides availability/cost	Yes	Very expensive		
Mechanization/access to suitable machinery	No			
Labor	No			
Transport	Yes	Very expensive		
Grain price/ marketing	No			
Conflict with other crop or livestock systems	Yes	Monocrop of soybeans, double crop wheat-soybean		

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	YES/NO	Description of constraint	Priority (Highest, high, moderate, low, not)	Approx investment required $
Field station operations (budget, land, staff, etc..)	No		Not	
Field machinery	Yes	Investment in equipment is needed (e.g., no tillage seeding machines, irrigation equipment)	High	
Technical assistance staff	Yes	Supporting personnel are needed	Highest	
Scientific expertise (genetics, pathology, agronomy, etc.)	No		Not	
Socioeconomic expertise (market & impacts analysis, etc.)	Yes	Low wheat prices and export taxes	Highest	
Labs/instruments (e.g., quality LAB, MAS, dryers, etc.)	Yes	Investment in equipment is needed	High	
Computers/software/GIS	Yes	Upgrading of computers and software is needed	Low	
Controlled growth environments	Yes	Investment in equipment is needed	Low	
Access to genetic resources/storage	Yes	Investment in equipment is needed	Moderate	
Training resources (classrooms, etc.)	Yes	Investment in equipment is needed	Low	
Transport	No		Not	
Resources to support collaboration & information sharing	Yes	Access to bibliographic resources	Moderate	
Other				

Table 5. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance 1-6*	Example of partnership Optional
Farmer groups	4	Joint ventures to multiply and distribute cultivars
Local private companies	3	Germplasm exchange, selection
International centers	1	Germplasm exchange, technical assistance and training
Foreign research institutions	2	Germplasm exchange, technical assistance and training
Multinationals	5	
NGOs	6	

*Raking (1=most important, 6=least important)

Table 6. Most useful /desirable outputs from CGIAR center

CIMMYT output	Specific out put	Priority
Germplasm		
Advanced lines with generic traits (yield, disease res. etc)	For high yield, resistance to diseases and specific industrial qualities.	Highest
Segregating bulks (F2 onwards)		Moderate
Genetic resources	For high yield, resistance to diseases and specific industrial qualities.	Highest
Training/knowledge sharing		
Basic training for younger scientists	Breeding, pathology and industrial quality	High
Advanced courses for mid-career scientists	Breeding, pathology and industrial quality	High
Specialized visits of individual scientists, e.g., to CIMMYT	Breeding, pathology and industrial quality	High
Visits of CIMMYT scientists to your program	Breeding, pathology and industrial quality	High
Methodologies/Information/Publications on		
Breeding (e.g., international nursery reports; IWIS, etc.)	For bread, durum and soft wheat	High
Pathology and pest control	fusarium head blight, rusts and leaf diseases	High
Genetics (quantitative and molecular)	Availability of molecular markers	Highest
Pre-breeding and genetic resources		Low
Physiology (crop and/or cellular)		Moderate
Statistics and experimental design	New methods to improve efficiency of evaluation of advanced lines.	High
Crop management		Low
Participatory methods		Moderate
Seed technolgy		Low
Social science and economic analysis		Low
Training methods		Moderate
Software support for databases, GIS, websites, etc.	Low price software to apply new technologies (AMMI, GEI).	Highest

Study of Local Wheat Genetic Resources in Azerbaijan

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Cereal production is one of the key areas of Azeri agriculture and wheat contributes significantly to cereal production. In this regard the development of high yielding and high quality wheat varieties resistant to biotic and abiotic environmental factors is very important. Durum and bread wheat collections from various regions of Azerbaijan are considered as rich botanical-geographical and valuable genetic resource for study. The study of these material allows to identify valuable forms useful for breeding activities. Our study focused on agronomic traits and of 154 durum wheat entries and 242 bread wheat entries. Early maturing durum wheat entries were found to make up to 9,6% of total germplasm studied. In the case of bread wheat it was 17,3%. All three types of spike density were found in durum wheat samples studied. About 55,2% of total durum wheat samples studied were found to have moderate ear density, 10,3% with dens ear and 34,5% with friable ear. But in bread wheat it made up 49,6%; 1,6%; and 47,8%, respectively. By plant height 6,7% of durum wheat samples studied was found short-stalked, 23% middle-stalked and 70,3% high-stalked, but in bread wheat it made up 9,5%, 40,6% and 44,5% respectively. For the percentage of kernels in the ear there was also substantial difference. In durum wheat the number of grain per spile ranged from 38 to 66 grains, but in bread wheat from 38 to 72 grains respectively. The ear kernel weight in durum wheat germplasm varied from 1,2 to 3,6 gr. and from 1,0 to 2,9 gr. in bread wheat. The 1000 kernel weight varied significantly both among varieties and within varieties. Thus, 1000 kernel weight in durum wheat fluctuated between 37,0-67,8 gram and in bread wheat samples 30,0-67,8 grams, respectively. Durum wheat yielded 415-640 gram/m^2, and bread wheat - 490-720 gram/m^2. The protein content varied 18,2-20,6% in durum wheat and 13,7-17,1% in bread wheat germplasm. As a result of studies 15 durum wheat and 20 bread wheat entries with valuable agronomic traits and characters were selected for further utilization in crop breeding activities.

Azerbaijan

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Table 1. Cultivars grown and released in irrigated and rainfed areas, 1955-present

(i) IRRIGATED AREAS

Period	**Modern varieties (MV)** *hectares sown*	**Landraces** *hectares sown*	**Avg MV yield** *t/ha*	**Avg landrace yield** *t/ha*	**Cultivars released** *number*	**Dominant variety 1** *hectares sown*	**Dominant variety 2** *hectartes sown*	**Avg farm size** *ha*
1995-2005	417,500 -802,300		1.5 - 2.65		11	Qiymatli 2/17 — 150th	Akinchi-84 —80th	
1985-1995	299,800 -417,500		1.5- 2.59		7	Mirbashir-50 —50th	Qaraqilchiq -2 —50th	
1975-1985	408,800 - 299,800		1.53 - 2.59			Mugan —15th	Bezostaya-1 —200th	
1965-1975	658,200 - 408,800		1.03 - 1.53			Bezostaya-1 —150th	Ferriqineum -20th	
1955-1965	658,200 - 820,200		0.75 -1.03			Ferriqineum - 50th	Shark —50th	

(ii) RAINFED AREAS

Period	**Modern varieties (MV)** *hectares sown*	**Landraces** *hectares sown*	**Avg MV yield** *t/ha*	**Avg landrace yield** *t/ha*	**Cultivars released** *number*	**Dominant variety 1** *hectares sown*	**Dominant variety 2** *hectartes sown*	**Avg farm size** *ha*
1995-2005			1.2 - 2.0					
1985-1995			2.0 - 1.1					
1975-1985			1.1 - 2.0					
1965-1975			0.7 - 1.0					
1955-1965			0.5 - 0.7					

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

(i) IRRIGATED AREAS

	Conventional tillage	**Reduced/zero tillage**	**Average N:P:K applied**	**Fully mechanized**	**Sown on flat**	**Sown on raised beds**	**Gravity:sprinkler irrigation**	**Irrigation applied**
2 yr period	***hectares sown***	***hectares sown***	***kg/ha***	***% of area***	***hectares sown***	***hectares sown***	***ratio***	***mm or frequency***
2004-2005	414,000 -427,700		54 -65	90	414,000 -427,700	1,000		180 - 192
2002-2003	412,800 -455,300		28-32	90	412,800 -455,300			175 -184
2000-2001	346,700 -400,000		25 -18	90	346,700- 400,000			150 -160
1998-1999	296,200 - 354,500		38 -43	90	296,200 - 354,500			190 -200
1996-1997	319,400 - 371,000		163 -144	90	319,400 - 371,000			185 - 195

(ii) RAINFED AREAS

	Conventional tillage	**Reduced/zero tillage**	**Average N:P:K applied**	**Fully mechanized**	**Annual cropping**	**Cereal-fallow**	**Weed control (grasses)**	**Broadleaf weeds**
2 yr period	***hectares sown***	***hectares sown***	***kg/ha***	***% of area***	***hectares sown***	***hectares sown***	***methods***	***methods***
2004-2005	177,500 -183,200		54-65	100	177,500 -183,200	10,000	chemical	chemical
2002-2003	176,900 - 195,100		28-32	100	176,900 - 195,100	125,000	chemical	chemical
2000-2001	149,000 - 171,100		25-18	100	149,000 - 171,100	87,000	chemical	chemical
1998-1999	127,000 -151,900		38-43	100	127,000 - 151,900	80,000	chemical	chemical
1996-1997	136,900 - 159,000		163-144	100	136,900 - 159,000	65,000z	chemical	chemical

Table 3. Current and emerging constraints to wheat production

Environmental constraint	**Yes/No**	**Description of constraint**	**Area affected**	**Typical yield loss**
Abiotic			***Hectares or % of total area***	***Range (%)***
Low rainfall	Yes	17.4% of territory receives 300 mm rainfall (at non-season period)	1,502,546	20-25
Declining water resources (for irrigation)	No			
Heat	Yes	Heat stress at grain filling period		20-25
Cold	No			
Salinization	Yes		30%	15-20
Soil physical degradation	No			
Micro-element deficiency (e.g., Zn, Bo)	No			
Micro-element toxicity (e.g., Al, Bo)	No			
Lodging	Yes	In some areas, but not at large scale		
Other	No			
Biotic				
Diseases	Yes	Smut. Rust diseases		3-5
Pests	Yes	Cereal bug, rodents		5-6
Weeds	Yes	Wild oats. Winter cress. Poor knowledge of farmers about weed control		
Socioeconomic constraint				
Credit	Yes	Insufficient credit resources		
Seed availability/quality	Yes	Shortage of high certified seed		20-25
Fertilizer availability	Yes	Lack of fertilizer, high price		20-25
Fungicide/pesticides/herbicides availability/cost	Yes	Lack of pesticides, high price		10-15
Mechaniztaion/ access to suitable machinery	Yes	Lack of new machinery, high price		15-20
Labor	No			
Transport	Yes	Transport shortage		
Grain price/ marketing	Yes	Low price of wheat, local market is not regulated		
Conflict with other crop or livestock systems	No			

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	Yes/No	Description of constraint	Priority	Approx investment required $
Field station operations (budget, land, staff, etc.)	Yes	Limited budget resources and skilled staff	Moderate	100,000
Field machinery	Yes	Lack of small-sized machinery	High	300,000
Technical assistance staff	No			
Scientific expertise (genetics, pathology, agronomy, etc.)	No			
Socioeconomic expertise (market & impacts analysis, etc.)	Yes	Market and impact analyses are not conducted due to lack of skilled staff	Moderate	30,000
Labs/instruments (e.g., quality LAB, MAS, dryers, etc.)	Yes	Lack of up-to-date lab. Equipment and tools	High	200,000
Computers/software/GIS	Yes	Lack of GIS	High	30,000
Controlled growth environments	No			
Access to genetic resources/storage	No			
Training resources (classrooms, etc.)	Yes	Lack of well-equipped Training Center	Moderate	50,000
Transport	Yes	Lack of transportation for breeding	Moderate	50,000
Resources to support collaboration & information sharing	Yes	Poor foreign language (English) skills of staff to share information and establish collaborations	High	50,000

Table 5. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance 1-6*	Example of partnership *Optional*
Farmer groups	3	Local farmer groups
Local private companies	4	Tavuz-Baltia, Ema, Farmer holdings Sabir
International centers	1	CIMMYT , ICARDA
Foreign research institutes	2	Washington State University
Multinationals	5	
NGOs		

*Ranking (1=most important, 6=least important)

Table 6. Most useful /desirable outputs from CGIAR centers

CIMMYT output	Specify	Priority
Germplasm		
Advanced lines with generic traits (yield, disease res., etc.)		High
Segregating bulks (F2 onwards)		
Genetic resources		Low
Training/knowledge sharing		
Basic training for younger scientists	At limited level	Moderate
Advanced courses for mid-career scientists	At more limited level	Moderate
Specialized visits of individual scientists, e.g., to CIMMYT	At more limited level	Low
Visits of CIMMYT scientists to your program		Moderate
Methodologies/Information/Publications on		
Breeding (e.g., international nursery reports, IWIS, etc.)		Low
Pathology and pest control		Moderate
Genetics (quantitative and molecular)		Low
Pre-breeding and genetic resources		Moderate
Physiology (crop and/or cellular)		Low
Statistics and experimental design		Not
Crop management		Low
Participatory methods		
Seed technology		Low
Social science and economic analysis		
Training methods		Not
Software support for databases, GIS, websites, etc.		Not

Wheat Production in Bangladesh - An Overview

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Wheat in Bangladesh is the second most important cereal next to rice. Before 1965, wheat was grown on a negligible area. During 1965-75, wheat expanded to over 0.11 million ha per year. About 38% of the area was covered with introduced varieties, including Kalyansona, Sonora 64 and Dirk. From 1975 to 1985, Government undertook a massive wheat expansion program and Wheat Research Center released eight high yielding varieties. Sonalika, introduced in 1974, covered about 68% of the 0.40 m ha planted. During 1985-1995, the high yield wheat area rose to 0.60 m ha per year. Among the high yielding varieties released during this period, Kanchan (released in 1983) became the most popular variety (on 54% area). During 1995-2005, the average wheat area was 0.73 m ha per year with a yield of 2.20 t/ha and Kanchan remained predominant on 80% of the wheat area. Wheat reached a maximum area of 0.88 m ha during 1998-99 with an average yield of 2.32 t/ha. Since then the area planted has declined by ± 30% due to competition from many alternative cool (Rabi) season crops. Yields have stagnated because of input constraints, disease pressure and probably global warming. Six high yield potential varieties (Sourav, Gourab, Shatabdi, Sufi, Bijoy and Prodip) have been released since 1998 and are very popular among farmers due to their high temperature tolerance, bold grains, and resistance to leaf rust and bipolaris leaf blight. They are gradually replacing Kanchan that has become susceptible to both diseases. At present, 80% of the wheat is under irrigation and 20% is grown on residual soil moisture. During the last decade, the use of farm machinery in wheat production has increased significantly. At present, 80% of the wheat is broadcast seeded after reduced tillage (2-3 passes) by power tiller that has replaced conventional tillage by a bullock-drawn plough. The area of wheat planted by power tiller operated seeder is also increasing. About 50% of the wheat is threshed by machine. In most cases, wheat is sown on flat land, with a negligible area on raised beds. Most wheat growers use less fertilizer, especially P and K, than the recommendation. Late planting (terminal heat stress), bipolaris leaf blight, spike sterility, and soil acidity are the major yield constraints in Bangladesh. Among these, high temperature during grain filling is the most important constraint. The light soils of the main wheat belt in northwestern Bangladesh are deficient in B causing spike sterility and acidic, fixing P in the soil. Wheat productivity can be raised through quick dissemination of new varieties, and improved crop management. Scope remains for area expansion. About 1.75 m ha remains fallow throughout the country after one monsoon rice crop due to lack of irrigation facilities or late receding of floodwater and some of this area could be planted to wheat, especially in the south. Wheat Research Center continues research programs on the above issues. CIMMYT has helped the wheat program of Bangladesh for around 30 years with the supply of germplasm, human resource development, and expertize which should be continued. CIMMYT offices in South Asia should be strengthened to meet the challenges of wheat research and development in Bangladesh.

Bangladesh

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Table 1. Cultivars grown and released in irrigated and rainfed areas, 1955-present

(i) IRRIGATED AREAS

	Modern varieties (MV)	Landraces	Avg MV yield	Avg landrace yield	Cultivars released	Dominant variety 1	Dominant variety 2	Avg farm size
Period	*hectares sown (ha)*	*hectares sown (ha)*	*t/ha*	*t/ha*	*number*	*hectares sown (ha)*	*hectares sown (ha)*	*ha*
1995-2005	436,000	nil	2.20	nil	6	(Kanchan) 0.35	[Shatabdi] 0.04	0.60 ha
1985-1995	300,000	nil	2.00	nil	3	[Kanchan] 0.17	[Sonalika] 0.126	0.70 ha
1975-1985	140,000	20,000	2.10	0.90	8	[Sonalika] 0.10	[Kalyansona] 0.02	0.90 ha
1965-1975	9,000	15,000	1.80	0.80	7	[Kheri] 0.006	[Kalyansona] 0.002	1.00 ha
1955-1965		Wheat was cultivated in negligible areas						

(ii) AREAS UNDER RESIDUAL SOIL MOISTURE

	Modern varieties (MV)	Landraces	Avg MV yield	Avg landrace yield	Cultivars released	Dominant variety 1	Dominant variety 2	Avg farm size
Period	*hectares sown (ha)*	*hectares sown (ha)*	*t/ha*	*t/ha*	*number*	*hectares sown (ha)*	*hectares own (ha)*	*ha*
1995-2005	290,000	nil	1.90	nil		(Kanchan) 0.23	[Shatabdi] 0.02	0.60 ha
1985-1995	300,000	nil	1.70	nil		[Kanchan] 0.17	[Sonalika] 0.126	0.70 ha
1975-1985	220,000	24,000	1.70	0.80	same as irrigated	[Sonalika] 0.16	[Kalyansona] 0.02	0.80 ha
1965-1975	35,000	58,000	1.65	0.70		[Kheri] 0.022	[Kalyansona] 0.008	1.00 ha
1955-1965		Wheat cultivation was negligible						

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

(i) IRRIGATED AREAS

	Conventional tillage [1]	Reduced/zero tillage [2]	Average N:P:K applied	Fully * mechanized	Sown on flat	Sown on raised beds	Gravity:sprinkler irrigation	Irrigation applied **
2 yr period	*hectares sown (ha)*	*hectares sown (ha)*	*kg/ha*	*% of area*	*hectares sown (ha)*	*hectares sown*	*ratio*	*mm or frequency*
2004-2005	110,000	340,000	80-60-20	Partially mechanized in different operations	450,000	Negligible	100	1 to 3
2002-2003	190,000	338,000	80-60-20		528,000	Negligible	100	1 to 3
2000-2001	220,000	326,000	80-60-20		546,000	Negligible	100	1 to 2
1998-1999	200,000	298,000	80-60-20		498,000	Negligible	100	1 to 2
1996-1997	180,000	180,000	80-60-20		359,000	Negligible	100	1 to 2

* Significant areas highly mechanized for land preparation (70-80% by power tiller), about 600 ha sown by power tiller operated seeder (PTOs), mechanized threshing in 50% areas.

** 1 Irrigation = 80-100mm

[1] Convetional tillage means tillage by bullock -drawn country plough upto 1990

[2] Reduced tillage means land preparation by power tiller (at present about 80% area of wheat)

(ii) AREAS UNDER RESIDUAL SOIL MOISTURE

							Both for irrigated and residual moisture	
	Conventional tillage	Reduced/zero tillage	Average N:P:K applied	Fully mechanized	Total cropped area/year	Cereal-fallow	Weed control (grasses)	Broadleaf weeds
2 yr period	*hectares sown (ha)*	*hectares sown (ha)*	*kg/ha*	*% of area*	*hectares sown*	*hectares sown*	*methods*	*methods*
2004-2005	30,000	80,000	60-40-20	Similar to irrigated			One hand weeding	One hand weeding/chemical
2002-2003	60,000	110,000	60-40-20				One hand weeding	One hand weeding/chemical
2000-2001	90,000	140,000	60-40-20				One hand weeding	One hand weeding
1998-1999	150,000	180,000	60-40-20				One hand weeding	One hand weeding
1996-1997	180,000	180,000	60-40-20				One hand weeding	One hand weeding

Table 3. Current and emerging constraints to wheat production

Environmental constraint	YES/NO	Description of constraint	Area affected	Typical yield loss
Abiotic			Hectares or % of total area	Range (%)
Low rainfall	No			
Declining water resources (for irrigation)	No			
Heat	Yes	Heat stress during grain filling causes forced maturity, reduces grain size and grain yield significantly	50%	20-25%
Cold	No			
Salinization	Yes	About 0.05 m ha in southern region, i.e., coastal belt is affected with soil salinity	0.05%	15-20%
Soil physical degradation	Yes	Puddling of soil during rice cultivation increases soil degradation, irrigation from shallow or deep tubewells deposits arsenic and other heavy metals		
Micro-element deficiency (e.g., Zn, Bo)	Yes	Light soil in the northwestern part of the country is deficient in Boron causing spike sterility	40%	10-15%
Micro-element toxicity (e.g., Al, Bo)	No			
Lodging	Yes	In some years hail storms cause lodging thereby affecting grain yield	15%	10-15%
Other				
Biotic				
Diseases	Yes	Bipolaris leaf blight, leaf rust and seedling blight	80%	15-20%
Pests	Yes	Rodents and stored grain pests	40%	10-15%
Weeds	Yes	Farmers are reluctant to weed the field at least once Echinocloa colonum (Khude Shyama), Chenopodium album (Bothua), Polygonum playbejum (Kakri)	70%	10-15%
Socioeconomic constraint				
Credit	Yes	Most of the wheat growers can't afford the initial investment for inputs, i.e., seeds, fertilizers, etc. due to lack of sufficient credit facilities	80%	20-25%
Seed availability/quality	Yes	Although 80% seed comes from farmers the, quality of seed is poor and mostly seed of old varieties are available with majority farmers		
Fertilizer availability	No			
Fungicide/pesticides/herbicides availability/cost	No			
Mechaniztaion/ access to suitable machinery	Yes	Small-scale mechanization already initiated but is not faster due to lack of sufficient manufacturing companies, credit facilities, promotional activities, etc.	80%	25-30%
Labor	Yes	Labor crisis in the harvesting of preceding rice crop and preparation of wheat seeding causes late planting of wheat	60%	20-30%
Transport	No			
Grain price/ marketing	No			
Conflict with other crop or livestock systems	Yes	Maize, potato, boro rice and winter vegetables are competing with wheat	40%	20-25%

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	YES/NO	Description of constraint	Priority	Approx investment required $
Field station operations (budget, land, staff, etc.)	Yes	Budget from GOB is insufficient for field operations	High	US$ 300,000
Field machinery	No			
Technical assistance staff	No			
Scientific expertise (genetics, pathology, agronomy, etc.)	No			
Socioeconomic expertise (market & impacts analysis, etc.)	No			
Labs/instruments (e.g., quality LAB, MAS, driyers, etc.)	Yes	Lack of a quality laboratory	High	US$ 100,000
Computers/software/GIS	No			
Controlled growth environments	Yes	No growth chamber is available to conduct improved research under controlled environments	High	US$ 100,000
Access to genetic resources/storage	No			
Training resources (classrooms, etc.)	No			
Transport	No			
Resources to support collaboration & information sharing	No			
Other				

Table 5. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance 1-6*	Example of partnership Optional
Farmer groups	1	Training, demonstration, participatory research, seed production through Extension Department and seed producing agencies
Local private companies	3	Seed production, manufacturing farm machinery
International centers	2	Germplasm exchange, human resources development and expertise
Foreign research institutions	2	Germplasm exchange, visits, training, etc.
Multinationals	4	Seminar/workshop, exchange visits
NGOs	4	Technology transfer, seed production, etc.

*Ranking (1=most important, 6=least important)

Table 6. Most useful /desirable outputs from CGIAR centers

CIMMYT output	Specify	Priority
Germplasm		
Advanced lines with generic traits (yield, disease res., etc.)	Advanced lines of bread wheat with high yield potential, terminal heat tolerance, disease & lodging tolerance, short duration, improved quality, etc. for wheat	High
Segregating bulks (F2 onwards)	F2 and onward segregating generations for ME5	Moderate
Genetic resources	Bread wheat germplasm that is effective against biotic/abiotic stresses, elite nurseries for durum and triticale	High
Training/knowledge sharing		
Basic training for younger scientists	3-6 month basic training on wheat improvement, disease and crop management, quality, etc.	High
Advanced courses for mid-career scientists	1-month advanced courses on wheat improvement, disease & crop management, quality breeding, molecular genetics, etc.	High
Specialized visits of individual scientists, e.g., to CIMMYT	Visiting scientists from Bangladesh to attend workshop/seminars and selecting germplasms at CIMMYT HQ and also NARS through CIMMYT regional/local office, etc.	High
Visits of CIMMYT scientists to your program	CIMMYT scientists from region and HQ should visit wheat research and development program of Bangladesh regularly. CIMMYT regional office including CIMMYT Bangladesh should be strengthened	High
Methodologies/Information/Publications on		
Breeding (e.g. international nursery reports; IWIS, etc.)	Quality analysis for advanced lines, expertise on wheat improvement	High
Pathology and pest control	Installation of misting system to inoculate spores, expertise	High
Genetics (quantitative and molecular)	Facility development for biotechnology lab	Moderate
Pre-breeding and genetic resources	Shuttle breeding facilities through CIMMYT regional program	High
Physiology (crop and/or cellular)	Expertise on physiological research from CIMMYT Bangladesh and CIMMYT HQ	High
Statistics and experimental design	New statistical packages, designs	Moderate
Crop management	Expertise in crop management from CIMMYT HQ and CIMMYT Bangladesh	High
Participatory methods	New methodologies	Moderate
Seed technolgy		Not
Social science and economic analysis	New statistical package for economic data analysis	Moderate
Training methods	Methodology	Moderate
Software support for databases, GIS, websites, etc.	New software for database	

The Brazil Country Survey

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The mean wheat sowing area in the last 10 years in Brazil is around 2 million hectares. Ninety percent is concentrated in the states of Paraná and Rio Grande do Sul and around 95 percent is cultivated under reduced or zero tillage sistems. The average yield is near to 1,800 kg ha^{-1} in rainfed areas and over than 4,500 kg ha^{-1} in irrigated areas (less than two percent of the brazilian area is sowed under irrigation, in the Savanas region). Most of the area is covered by modern cultivars and less than one percent is sown with landraces. The breeding programs in Brazil released 429 wheat cultivars for the different production regions since 1922.

The current abiotic constraints are: low rainfall (drought) and heat stress at the Brazilian Savanas region; and lodging, cold (frost) and pre-harvest sprouting in the Southern Brazil. The most important diseases are: leaf rust (*Puccinia triticina*); scab (*Fusarium graminearum*); mildew (*Blumeria graminis*); glume blotch (*Stagonospora nodorum*); tan spot (*Drecshlera tritici repentis*); spot blotch (*Bipolares sorokiniana*)(*Helminthosporium sativum*); head blast (rice blast) (*Magnaporthe grisea*); and virus diseases (Barley Yellow Dwarf Virus and Soil borne Mosaic Virus).

Brazil

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Table 1. Cultivars grown and released in irrigated and rainfed areas, 1955-present

(i) IRRIGATED AREAS

Period	Modern varieties (MV) hectares sown	Landraces hectares sown	Avg MV yield t/ha	Avg landrace yield t/ha	Cultivars released number	Dominant variety 1 hectares sown	Dominant variety 2 hectartes sown	Avg farm size ha
1995-2005	18,500	0	4.5	0	11			
1985-1995	35,000	0	3.4	0				
1975-1985	1,000	0	<3	0				
1965-1975	1,000	<1%	<3	0.8				
1955-1965	1,000	<1%	<3	0.8				

(ii) RAINFED AREAS

Period	Modern varieties (MV) hectares sown	Landraces hectares sown	Avg MV yield t/ha	Avg landrace yield t/ha	Cultivars released number	Dominant variety 1 hectares sown	Dominant variety 2 hectartes sown	Avg farm size ha
1995-2005	1,835,074	<1%	1.8	1.5	73	170,830	140,830	
1985-1995	2,459,756	<1%	1.5	1.2	83	687,500	332,500	
1975-1985	2,820,960	<1%	0.9	1	86	389,000	358,300	
1965-1975	1,622,985	<1%	0.8	1	39	250,000	191,600	
1955-1965	303,891	<1%	0.6	<1	28			

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

(i) IRRIGATED AREAS

2 yr period	Conventional tillage *hectares sown*	Reduced/zero tillage *hectares sown*	Average N:P:K applied *kg/ha*	Fully mechanized *% of area*	Sown on flat *hectares sown*	Sown on raised beds *hectares sown*	Gravity:sprinkler irrigation *ratio*	Irrigation applied *mm or frequency*
2004-2005	6,400	25,600	450 kg/ha (2-25-25)	100			0:100	450 mm - 110 days
2002-2003	12,000	13,000	(+ 170kg/ha N	100			0:100	distributed weekly
2000-2001	18,500	2,100	in 3 applications)	100			0:100	
1998-1999	14,000			100			0:100	
1996-1997	9,600			100			0:100	

(ii) RAINFED AREAS

2 yr period	Conventional tillage *hectares sown*	Reduced/zero tillage *hectares sown*	Average N:P:K applied *kg/ha*	Fully mechanized *% of area*	Annual cropping *hectares sown*	*Cereal-fallow*	Weed control (grasses) *methods*	Broadleaf weeds *methods*
2005	255,057	8,246,836	250 kg/ha (5-25-20)	100			Herbicides	Herbicides
2004	466,355	8,860,382	(+ 60 kg/ha N in	100			Herbicides	Herbicides
2003	745,822	6,712,399	one application)	100			Herbicides	Herbicides
2002	1,492,207	5,968,829		100			Herbicides	Herbicides
2001	2,547,483	3,821,224		100			Herbicides	Herbicides
2000							Herbicides	Herbicides

Table 3. Current and emerging constraints to wheat production

Environmental constraint Abiotic	Yes/No	Description of constraint	Area affected (potential) *Hectares or % of total area*	Typical yield loss *Range (%) (potential)*
Low rainfall	No	Problems less than 1% in savannas region	< 1%	50-80%
Declining water resources (for irrigation)	Yes	Restrictive governmental politics		
Heat	Yes	Some problems in non-irrigated savanna conditions	< 5%	50-80%
Cold	Yes	Serious problems in southern Brazil in some years	30%	100%
Salinization	No	Problems less than 1% in savannas region	< 1%	50-80%
Soil physical degradation	No			
Micro-element deficiency (e.g., Zn, Bo)	Yes	Boron in savanna region	< 1%	50%
Micro-element toxicity (e.g., Al, Bo)	Yes	Problems with Mn and Al specially in dry conditions in southern Brazil	10%	30%
Lodging	Yes	Tall genotypes	10%	20%
Other	Yes	Pre-harvest sprouting	50%	100%
Biotic				
Diseases	Yes	Puccinia triticina, Giberela zeae/Magnaporthe grisea, Dreschlera tritice/Bipolaris sorokiniana/ 80% 30%		
Pests	Yes	Aphids (green bug - VNAC), caterpillars,	80%	0%
Weeds	Yes	Lollium multiflorum, avena strigosa, Cenchrus echinatus, Raphanus raphanistrum, Poligonum sp., Bidens pilosa 20% 20%		
Socioeconomic constraint				
Credit	Yes	Late liberation sources		
Seed availability/quality	No			
Fertilizer availability	No			
Fungicide/pesticides/herbicides availability/cost	Yes	High costs		
Mechanization/access to suitable machinery	Yes	High cost of zero tillage machines		
Labor	No			
Transport Yes High cost of transport				
Grain price/ marketing	Yes	Production cost/low selling prices/no segregation of hard and soft wheats		
Conflict with other crop or livestock systems	No			

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	Yes/No	Description of constraint	Priority (Highest, high, moderate, low, not)	Approx investment required $
Field station operations (budget, land, staff, etc.)	Yes	Low budget	Moderate	
Field machinery	Yes	High cost of field machines	-	
Technical assistance staff	Yes	Low training of technical assistance staff	Moderate	
Scientific expertise (genetics, pathology, agronomy, etc.)	Yes	Retirement of governmental scientists and no repositioning of them	-	
Socioeconomic expertise (market & impacts analysis, etc.)	No	No skilled researchers in some departments	High	
Labs/instruments (e.g. quality LAB, MAS, dryers, etc.)	Yes	Low number of specialized labs	High	
Computers/software/GIS	No		-	
Controlled growth environments	Yes	Field resources	-	
Access to genetic resources/storage	Yes	Limited access to genetic resources	Moderate	
Training resources (classrooms, etc.)	Yes	Low budget for training	Moderate	
Transport	Yes	High cost	High	
Resources to support collaboration & information sharing	Yes	Low budget	Moderate	
Other	Yes	Subsidies practices	High	
Other	Yes	High cost of local production		

Table 5. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance 1-6*	Example of partnership Optional
Farmer groups	2	Pro-Sementes, Meridional and Vegetal Foundations; Cooperatives
Local private companies	1	Coodetec, Fundacep/Fecotrigo, OR Sementes
International centers	2	CIMMYT and ICARDA
Foreign research institutions	-	-
Multinationals	3	Bayer Crop Science, Basf, Du Pont, Monsanto, Syngenta, FMC, Bunge, Cargil
NGOs	-	-
Governmental institutes	1	Embrapa, IAPAR, IAC, FEPAGRO, EPAMIG, EPAGRI and Federal Universities

*Ranking (1=most important, 6=least important)

Table 6. Most useful /desirable outputs from CGIAR centers

CIMMYT output	Specify	Priority
Germplasm		
Advanced lines with generic traits (yield, disease res., etc.)		High
Advanced lines with generic traits (yield, disease res., etc.)	Bread quality, yield, diseases resistance (mainly Bipolaris, Giberela zea, Puccinia triticina and Magnaporthe grisea)	High
Segregating bulks (F2 onwards)	F2 and advanced lines	High
Genetic resources	Bread quality, yield, diseases resistance (mainly Bipolaris, Giberela zea, Puccinia triticina and Magnaporthe grisea)	High
Training/knowledge sharing		
Basic training for younger scientists	Advanced wheat breeding	High
Advanced courses for mid-career scientists	Quality, breeding, biotechnology and physiology	High
Specialized visits of individual scientists, e.g., to CIMMYT	Opportunity to visit special programs	High
Visits of CIMMYT scientists to your program	Opportunity to discuss advanced knowledge	High
Methodologies/Information/Publications on		
Breeding (e.g., international nursery reports; IWIS, etc.)	International nursery reports	Moderate
Pathology and pest control	New technologies in research	Moderate
Genetics (quantitative and molecular) Training High		
Pre-breeding and genetic resources	Information of new available genes	High
Physiology (crop and/or cellular)	Information of new knowledge	High
Statistics and experimental design	New statistics models	Moderate
Crop management	-	Low
Participatory methods	Training	Moderate
Seed technology - Low		
Social science and economic analysis	-	Low
Training methods	-	Low
Software support for databases, GIS, websites, etc.	-	Low

Priority and Challenge of Wheat Production in China

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China produces around 95 million tons of wheat with sowing area of 23 million ha. Averaged wheat yield has risen from 1.0 to 3.9 t/ha, largely due to deployment of improved cultivars and management practices, and increased inputs in fertilizers, and mechanization. Further improvement of yield potential with acceptable quality, and reduced inputs are needed to meet the consumption demand. The major biotic stresses of wheat production include powdery mildew, stripe rust. *Fusarium* head scab, sharp eyespot, take all, and aphid. Decline of water resources, and heat after anthesis, and cold are the most important abiotic stresses. Small farmer size, low grain price, weak extension system, and shift to high value cash crops, could potentially slow down wheat production. Enhanced germplasm, training, and information from CIMMYT are crucial to Chinese breeding programs. Integration of various disciplines such as breeding, biotechnology, pathology, cereal quality, and agronomy are urgently needed to improve breeding efficiency.

China

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Table 1. Cultivars grown and released in irrigated and rainfed areas, 1955-present

(i) IRRIGATED AREAS

Period	Modern varieties (MV) *% of area*	Landraces *% of area*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *% of area*	Dominant variety 2 *% of area*	Avg farm size *ha*
1995-2005	100%	Not used	5.5	Not used	600	Yumai 18	Yumai 21	0.7
1985-1995	100%	Not used	5	Not used	450	Bainong 3217	Yangmai 5	0.7
1975-1985	100%	Not used	4.5	Not used	300	Taishan 1	Fengchan 3	20
1965-1975	100%	Not used	4	Not used	150	Neixiang 5	Jinan 2	20
1955-1965	90%	10%	3.5	3	100	Bima 1	Nanda 2419	20

(ii) RAINFED AREAS

Period	Modern varieties (MV) *% of area*	Landraces *% of area*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *% of area*	Dominant variety 2 *% of area*	Avg farm size *ha*
1995-2005	100%	0%	3.2	Not used	50	Jinmai 47	Luohan 2	1.2
1985-1995	100%	0%	3	Not used	30	Jinmai 33	Weimai 5	1.2
1975-1985	95%	5%	2.5	2	20	Changle 5	Beijing 10	20
1965-1975	80%	20%	2	1.5	20	Jinan 2	Beijing 8	20
1955-1965	50%	50%	2	1.5	15	Youzimai	Xuzhou 438	20

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

(i) IRRIGATED AREAS

2 yr period	Conventional tillage *hectares sown*	Reduced/zero tillage *hectares sown*	Average N:P:K applied *kg/ha*	Fully mechanized *% of area*	Sown on flat *hectares sown*	Sown on raised beds *hectares sown*	Gravity:sprinkler irrigation *ratio*	Irrigation applied *mm or frequency*
2004-2005	9,611,600	4,805,800	140 90 45	90	4,325,220	10,092,180	40/60	100-120mm
2002-2003	8,798,840	5,865,893	130 90 45	85	4,399,420	10,265,313	50/50	100-120mm
2000-2001	10,687,330	5,754,933	120 80 45	80	4,932,800	11,509,866	60/40	100-120mm
1998-1999	11,549,758	6,219,100	120 75 45	70	5,330,658	12,438,202	65/35	100-120mm
1996-1997	14,026,600	6,011,416	110 75 30	70	6,011,416	14,026,600	70/30	100-120mm

(ii) RAINFED AREAS

2 yr period	Conventional tillage *hectares sown*	Reduced/zero tillage *hectares sown*	Average N:P:K applied *kg/ha*	Fully mechanized *% of area*	Annual cropping *hectares sown*	Cereal-fallow *hectares sown*	Weed control (grasses) *methods*	Broadleaf weeds *methods*
2004-2005	4,325,220	2,883,480	120 90 15	40	6,487,830	720,870	Use herbicides	
2002-2003	4,399,420	2,932,946	120 90 15	40	6,599,130	733,236	Use herbicides	
2000-2001	5,343,866	2,877,466	120 90 10	30	7,399,199	822,133	Use herbicides	
1998-1999	5,922,953	2,961,476	105 90 10	30	7,995,987	888,442	Use herbicides	
1996-1997	6,679,351	3,339,675	90 75 10	20	8,929,526	1,086,500	Use herbicides	

Table 3. Current and emerging constraints to wheat production

Environmental constraint	YES/NO	Description of constraint	Area affected	Typical yield loss
Abiotic			***Hectares or % of total area***	***Range (%)***
Low rainfall	Yes	Especially in Shanxi, Gansu province	20% of total area	20%~30%
Declining water resources (for irrigation)	Yes	Especially in Hebei, Shandong, Henan province	50% of total area	10%~20%
Heat	Yes	High temperature during grain filling stage	70% of total area	3-5%
Cold	No	Spring type wheat was planted in Yellow and Huai valley. This resulted in winterkill.		
Salinization	No	Minor problem in Inner Mongolia and Xinjiang		
Soil physical degradation	No			
Micro-element deficiency (e.g., Zn, Bo)	No			
Micro-element toxicity (e.g., Al, Bo)	No			
Lodging	Yes	In some areas, but not at large scale		
Other	No			
Biotic				
Diseases	Yes	Powdery mildew, head scab, sharp eyespot, yellow rust.	70%, 30%, 50%, 20%	10-20%
Pests	Yes	Aphid, chemicals were applied 3-4 times	60%	Difficult to estimate since chemicals must be applied
Weeds	Yes	Avena fatua L., Alopecurua aequalis Sobol., Malachium aguativum (L.) Fries	45%	15%
Socioeconomic constraint				
Credit	No			
Seed availability/quality	No			
Fertilizer availability	Yes	It is available, but quality is not consistent, and price is high		
Fungicide/pesticides/herbicides availability/cost	No			
Mechanization/ access to suitable machinery	Yes	Not available in some areas		
Labor	No			
Transport	No			
Grain price/ marketing	Yes	Price is very low, and farmers interest is turning to other high value cash crops		
Conflict with other crop or livestock systems	Yes	More vegetables and fruits to replace wheat		

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	YES/NO	Description of constraint	Priority *(Highest, high, moderate, low, not)*	Approx investment required $
Field station operations (budget, land, staff etc.)	Yes	Field station used for building new house	High	Need government support policy
Field machinery	Yes	No funding to buy it, it is difficult to run the machine in south China	Highest	180K US$ per set
Technical assistance staff	Yes	Trained professionals unwilling to do field work, most field work done by labor	High	Government policy
Scientific expertize (genetics, pathology, agronomy etc)	Yes	Lack of pathology support for breeding, agronomy has declined	Highest	Government policy
Socioeconomic expertise (market & impacts analysis, etc.)	Yes	Seed marketing analysis	Moderate	
Labs/instruments (e.g., quality LAB, MAS, dryers, etc.)	Yes	Shortage of cereal chemists to operate the lab	Highest	
Computers/software/GIS	No			
Controlled growth environments	Yes	Greenhouse facility and management	Moderate	
Access to genetic resources/storage	Yes	Unwilling to share	High	
Training resources (classrooms, etc.)	Yes	Need for international training	High	
Transport	No			
Resources to support collaboration & information sharing	Yes	Government does not have funding to support it. Leading scientists spend most of their time fundraising. Interdisciplinary cooperation is difficult, especially among breeders, biotechnologists, agronomists, and soil scientists. Resource allocation to crop management is extremely low in relative terms, compared to breeding and biotech.	Highest	Inapproximate policy after 1990
Other	Yes	International collaboration.	High	

Table 5. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance *1-6**	Example of partnership *Optional*
Farmer groups	1	For seed increase and pilot trials
Local private companies	3	Agreement for marketing new varieties
International centers	1	CIMMYT for training and providing germplasm, unfortunately largely reduced or stopped
Foreign research institutes	4	China-Australia cooperation on BYDV, quality
Multinationals	5	
NGOs	6	

*Ranking (1=most important, 6=least important)

Table 6. Most useful /desirable outputs from CGIAR centers

CIMMYT output	Specify	Priority
Germplasm		
Advanced lines with generic traits (yield, disease res., etc.)	Yield , disease resistance and quality	Highest
Segregating bulks (F2 onwards)	Not so important	Low
Genetic resources	For breeding and special study	High
Training/knowledge sharing		
Basic training for younger scientists	Wheat improvement and quality course	Highest
Advanced courses for mid-carear scientists	Wheat improvement and quality course, pathology	Highest
Specialized visits of individual scientists, e.g., to CIMMYT	Understanding of CIMMYT approach and germplasm	High
Visits of CIMMYT scientists to your program	Understanding the needs and providing continued support	Highest
Methodologies/Information/Publications on		
Breeding (e.g., international nursery reports; IWIS, etc.)	Most people can not read it due to language difficulties	Moderate
Pathology and pest control	Wheat disease manual very useful since not much pathology support is available in China	Highest
Genetics (quantitative and molecular)	Not so important, but may establish linkage with advanced institutes through CIMMYT	Moderate
Pre-breeding and genetic resources	Not so important	Low
Physiology (crop and/or cellular)	Need field physiology support to work on yield potential and stress tolerance since most work on physiology is far away from breeding trials	High
Statistics and experimental design	Field design and data analysis (for example, a-latnized lattice) are urgently needed, most researcher still use RBD	Highest
Crop management	Use of nitrogen, reduced tillage, etc.	Highest
Participatory methods	Not so important, we have done it for many years	Not
Seed technolgy	Not so important since it is not CIMMYT's comparative advantage area	Low
Social science and economic analysis	World wheat facts and trends/overview and outlook are widely used.	Highest
Training methods	Not so important	Low
Software support for databases, GIS, websites, etc.	Needed by a few institutes	Moderate

Egypt

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Table 3. Current and emerging constraints to wheat production

Environmental constraint	YES/NO	Description of constraint	Area affected	Typical yield loss
Abiotic			*hectares or % of total area*	*range (%)*
Low rainfall		North coast under rainfed conditions		
Declining water resources (for irrigation)	Yes	In new reclaimed areas (sandy and calcareous soils)		
Heat	Yes	Terminal heat stress during grain filling in Upper Egypt		
Cold				
Salinization	Yes	In 30% of area		
Soil physical degradation				
Micro-element deficiency (e.g., Zn, Bo)				
Micro-element toxicity (e.g., Al, Bo)				
Lodging				
Other				
Biotic				
Diseases	Yes	Yellow rust, leaf rust, stem rust; race identification of the pathogens;		
Pests	Yes	Aphid		
Weeds	Yes	Wild oat		
Socioeconomic constraint				
Credit				
Seed availability/quality				
Fertilizer availability				
Fungicide/pesticides/herbicides availability/cost				
Mechanization/access to suitable machinery				
Labor				
Transport				
Grain price/ marketing				
Conflict with other crop or livestock systems				

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	YES/NO	Description of constraint	Priority (Highest, high, moderate, low, not)	Approx investment required $
Field station operations (budget, land, staff, etc.)	Yes	Limited area	Highest	
Field machinery				
Technical assistance staff				
Scientific expertise (genetics, pathology, agronomy, etc.)	Yes	Lack of application of recommended package; identification of genes for resistance to rusts; identification of sources of genes for various resistances	High	
Socioeconomic expertise (market & impacts analysis, etc.)				
Labs/instruments (e.g., quality LAB, MAS, driyers, etc.)				
Computers/software/GIS				
Controlled growth environments				
Access to genetic resources/storage				
Training resources (classrooms, etc.)				
Transport				
Resources to support collaboration & information sharing				
Other				

Table 5. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance *1-6**	Example of partnership *Optional*
Farmer groups		
Local private companies		
International centers	1	CIMMYT, ICARDA,
Foreign research institutions		
Multinationals		
National organizations	2	ARC-Egypt institutes including Plant Pathology Research Institute; Plant Protection Research Institute; Soil, Water and Environmental research Institute; Food Technology Research Institute; Central Laboratory for Weed Conservation Resarch; and Central Adminstration of Agricultural Extension

* Ranking (1=most important, 6=least important)

Table 6. Most useful /desirable outputs from CGIAR centers

CIMMYT output	Specify	Priority
Germplasm	***Germplasm exchange***	
Advanced lines with generic traits (yield, disease res. etc)		Highest
Segregating bulks (F2 onwards)		
Genetic resources	Source of genes for resistance	High
Training/knowledge sharing		
Basic training for younger scientists	In breeding, agronomy, physiology	High
Advanced courses for mid-career scientists	In breeding, agronomy, physiology	High
Specialized visits of individual scientists, e.g., to CIMMYT	Visits for breeders, agronomist, physiologists	High
Visits of CIMMYT scientists to your program		
Methodologies/Information/Publications on		
Breeding (e.g. international nursery reports; IWIS, etc.)		
Pathology and pest control	Identification of pathogen races	
Genetics (quantitative and molecular)	Identification of genes for rust resistance in local materials	
Pre-breeding and genetic resources	Screening and testing materials in rust hot spots	
Physiology (crop and/or cellular)	Crop physiology	
Statistics and experimental design		High
Crop management		
Participatory methods		
Seed technology		
Social science and economic analysis		
Training methods		
Software support for databases, GIS, websites, etc.		High

Challenges of Wheat Production in Ethiopia

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Ethiopia is the second largest producer of wheat in sub-Saharan Africa. Wheat is the fifth most important cereal crops in Ethiopia in terms of area of production and 2nd to maize in productivity. It comprises more than 15% of the total cereal outputs. In Ethiopia, two types of wheat species are dominantly grown as rain fed crops. The current total area of production of both durum wheat and bread wheat is about one million hectares. This area is limited to the intermediate and high altitude production zones despite a potential for irrigated wheat production in lowlands. Both durum and bread wheat types hold almost equal proportions. In area coverage, however, since the last 5-10 years the area coverage and production of bread wheat is increasing. Other wheat species such as Emmer wheat is also cultivated to a limited extent.

Over the last fifty years, the area coverage of modern wheat varieties was limited. Although no estimated figures were obtained for area coverage of improved varieties during the first two decades, there had been a slight increments both in area coverage and total grain yield during the last thirty years. The increase in production during the later years may be attributed to the increase in area coverage and improved crop management practices. For the period from 1975 to 2004 the area coverage of modern varieties was increased by about 10% (63 thousand to 70 thousand ha) on the other hand the increase in crop yield per hectare over the same period remained marginal, despite the fact that the yield potential of modern varieties has been increased two to three fold.

So far the national wheat research program in Ethiopia has developed and released 40 in bread wheat, 22 in durum wheat and one in Emmer wheat since the last forty years of which more than 60% are under production. There are also many improved wheat crop management practices tested and released in the area of agronomy, crop protection, fertilizer management, etc. Extension and demonstration packages undertaken by national institutes have demonstrated that wheat crop yields can be easily tripled with the use of improved seeds and crop management practices. However, in the Ethiopian condition both past and present, the overwhelming majority of farmers, rely on landrace varieties and unimproved management practices. As a result the productivity of wheat crops did not show significant improvement over the years, although there were success stories for bread wheat. Major causes reported for the low level of productivities are low use of improved varieties due to high price, little or no use of modem agricultural inputs and improved management practices (for instance improved tillage practices), decline in soil fertility, pest problems, environmental degradation and recurrent drought and the scarcity of suitable technologies to unfavorable environments.

Ethiopia

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Table 1. Cultivars grown and released in irrigated and rainfed areas, 1955-present

(i) IRRIGATED AREAS

Period	Irrigated areas *hectares sown*	%	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	2,670	0.35	NE		NE			
1985-1995	2,545	0.45	"		"			
1975-1985			"		"			
1969-1975			"		"			
1955-1965			"		"			

(ii) RAINFED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*		Avg landrace yield *t/ha*	Cultivars released *number*			Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*
			BW	DW		BW	DW	EW		
1995-2005	69,620	960,395	2.59	2.23	1.30	21	13	1	27,360	18,226
1985-1995	51,486	658,240	2.71	2.00	1.25	3	6	0	25,238	14,241
1975-1985	62,970	695,262	2.45	1.96	1.07	4	13	0	37,152	16,214
1969-1975	NE	966,162	2.10	1.73	7.5	2	10	0		
1955-1965	NE	650,400			7.01					

NE= Not Estimated; BW= Bread Wheat; DW= Durum Wheat; EW= Emmer Wheat

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

(i) IRRIGATED AREAS

2 yr period	*Conventional tillage hectares sown*	*Reduced/zero tillage hectares sown*	*Average N:P:K applied kg/ha*	*Fully mechanized % of area*	*Sown on flat hectares sown*	*Sown on raised beds hectares sown*	*Gravity:sprinkler irrigation ratio*	*Irrigation applied mm or frequency*
2004-2005	*	*	*	*	*	*	*	*
2002-2003	*	*	*	*	*	*	*	*
2000-2001	*	*	*	*	*	*	*	*
1998-1999	*	*	*	*	*	*	*	*
1996-1997	*	*	*	*	*	*	*	*

(ii) RAINFED

2 yr period	Conventional tillage *hectares sown*	Reduced/zero tillage *hectares sown*	Average N:P:K applied *kg/ha*	Fully mechanized *% of area*	Annual cropping *hectares sown*	Cereal-fallow *hectares sown*	Weed control (grasses) *methods*	Broadleaf weeds *methods*
2004-2005	Almost all	Insignificant	11.4: 29.04	13.1			Hand/conventional	Chemical/conventional
2002-2003	Almost all	"	10.5: 25.03	12.4			Hand/conventional	Chemical/conventional
2000-2001	All	None	13.7:23.2	11.03			Hand/conventional	Hand/conventional
1998-1999	All	"	16.6:26.7	11.04			Hand/conventional	"
1996-1997	All	"	19.1:30.2	10.92			Hand/conventional	"

* Insignificant

Table 3 Current and emerging constraints to wheat production

Environmental constraint	YES/NO	Description of constraint	Area affected	Typical yield loss
Abiotic			***Hectares or % of total area***	***Range (%)***
Low rainfall	Yes	Low rainfall and poor distribution	Low land area	20-30%
Declining water resources (for irrigation)	Yes	Poor soil and water conservation		NE
Heat	Yes	High temperature stress	Low altitudes	NE
Cold	Yes	Susceptible to frost	Highland areas	"
Salinization	No			
Soil physical degradation	Yes	Soil erosion	Lowland area 85%	NE
Micro-element deficiency (e.g., Zn,Bo)	Yes	Zn deficiency	65%	NE
Micro-element toxicity (e.g., Al, Bo)	No			
Lodging	Yes	Tall type durum wheat varieties and landraces are dominant	50%	10-15%
Other	Yes	High rainfall (waterlogging) stress	Highland areas	
Biotic				
Diseases	Yes	Yellow rust stem rust and septoria tritici		
	Yes	Shoot fly, aphid and storage pests (Weevils		
Weeds	Yes	Broadleaf: Commelina benghalensis, Scorpiurvs muricatus, Guzotia scabra Grasses: Lolium temulantum, Avena abyssinica, Avena fatula		
Socioeconomic constraint				
Credit	Yes	Insufficient number of credit associations for agricultural sectors		
Seed availability/quality	Yes	Insufficient availability of improved seed, low yield of durum wheat, and high cost of improved seeds		
Fertilizer availability	Yes	High cost and not available in timely manner		
Fungicide/pesticides/herbicides availability/cost	Yes	High cost and not sufficiently available		
Mechanization/access to suitable machinery	Yes	Not sufficiently mechanized, high cost of machinery		
Labor	No			
Transport	Yes	Poor infrastructure		
Grain price/marketing	Yes	Relative low price of wheat because of low grain quality and no markets		
Conflict with other crop or livestock systems	Yes	Resource sharing and competition with high value crops and livestock, and low price		

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	YES/NO	Description of constraint	Priority *(Highest, high, moderate, low, not)*	Approx investment required $
Field station operations (budget, land staff, etc.)	Yes	Senior staff shortage and training	High	
Field machinery	Yes	Farm implements (thresher tractors)	Medium	
Technical assistance staff	Yes	Training	High	
Scientific expertise (genetics, pathology, agronomy, etc.)	Yes	Genetics, biotechnology and stress physiology, race identification	Highest	
Socioeconomic expertise (market impacts analysis, etc.)	Yes	Impact analysis	High	
Labs/instruments(e.g., quality LAB. MAS. Dryers, etc.)	Yes	Quality laboratory	Highest	
Computers. software/GIS	Yes	Software/GIS	High	
Controlled growth environments	Yes	Greenhouse	High	
Access to genetic resources/storage	Yes	Storage	Medium	
Training resources (classrooms, etc.)	Yes	Classrooms and audiovisual	Low	
Transport	Yes	Vehicle	High	
Resources to support collaboration & information sharing	Yes	IT and internet	High	
Other	Yes	Maintenance of equipment	Moderate	

Table 5. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance *1-6**	Example of partnership *Optional*
Farmer groups	2	Extension, participatory research, and seed multiplication; germplasm maintenance
Local private companies	5	Research participation and seed multiplication
International centers	1	Capacity building, germplasm exchange, and sharing senior expertise; generation of new technologies
Foreign research institutions	6	Research support and capacity building
Multinationals	3	Credit and input supply
NGOs	4	Research and development, capacity building

*Ranking (1=most important, 6=least important)

Table 6. Most useful/desirable outputs from CGIAR centers

CIMMYT output	Specify *(Highest, high, moderate, low, not)*	Priority
Germplasm		
Advanced lines with generic traits (yield, disease res., etc.)	Yield, disease resistance, heat and moisture resistance	Highest
Segregating bulks (F2 onwards)	F2, F3 and superior segrates	High
Genetic resources	Genetic variability and information	High
Training/knowledge sharing		
Basic training for younger scientists	Biotechnology, physiology, and pathology	Highest
Advanced courses for mid-career scientists	Biometrics genetics/breeding, GIS	High
Specialized visits of individual scientists, e.g., to CIMMYT	Genetics/Breeding	High
Visits of CIMMYT scientists to your program	Breeding, pathology and biotechnology	High
Methodologies/Information/Publications on		
Breeding (e.g., international nursery reports; IWIS, etc.)	IWIS	High
Pathology and pest control	Methodology on loss assessment and race identification	High
Genetics (quantitative and molecular)	Methodology and information	High
Pre-breeding and genetic resources	Methodology and information	High
Physiology (crop and/or cellular)	Screening methods and publications/information	High
Statistics and experimental design	Information and publications	Moderate
Crop management	Screening methods and information	High
Participatory methods	Methodology	High
Seed technology	Methodology	High
Social science and economic analysis	Impact analysis methods and information	High
Training methods	Information	Moderate
Software support for databases, GIS, websites, etc.	GIS and websites	High

Yield Potential Survey – India

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India has firmed up its position as the second largest producer of wheat, in the world, only next to China harvesting 72.0 million tones during last crop season from an area of about 26.5 million hectare with a productivity of 2.7t/ha. The area under wheat crop in India has been hovering around 26-27 million ha for last ten years period maintaining the total production level above 70 million tones. It is also worth to mention here that the weather conditions during this decade also witnessed unusual changes during the wheat crop season which resulted in comparatively reduced growth. The availability of new and diverse varieties provided a mosaic suited to different production technologies that could sustain the productivity levels. The average productivity of wheat is quite high in high production areas of Punjab (4.2 t/ha) and Haryana (4.0 t/ha) with farmers achieving record production of 6 to 7 t/ha in certain areas of Punjab. Frontline demonstrations have indicated that there is a vast scope to enhance the productivity in the States of Uttar Pradesh, Madhya Pradesh, Bihar, Gujarat and Maharashtra.

The Directorate of Wheat Research is the nodal institution for coordinating the multidisciplinary and multi-location testing of wheat and barley technologies under AICW&BIP with the active support from a large number of funded and voluntary centres across the six mega zones of the country. Since 1965, nearly 312 wheat varieties have been developed to suit the various production conditions of six major wheat growing zones of the country. Since the advent of Green revolution in 1965 there had been a marked increase in the area and productivity of wheat. Besides other factors like expansion of irrigation facilities and 'pro-farmer' government's policies, the rate of the adoption of dwarf, photo-insensitive and nutrient responsive modern varieties by the farmers resulted in large areas being occupied by such varieties. Some of the high yielding landmarkvarieties like Kalyansona, Sonalika, Lerma Rojo, WL 711, WH 147, C 306, Lok1, HD 2009 and HD 2329 were very popular and widely grown by the farmers. PBW 343, a ruling variety for irrigated, timely sown condition of northwestern plains occupies 6 mha area and is currently the ruling variety. Other varieties like Lok 1, HUW 234 and UP 262, though now susceptible to rusts are still a favourite amongst farmers.

One of the major concerns of wheat researchers is to make Indian wheat globally competitive by reducing the cost of cultivation and increasing farmer's profitability. India has made concerted efforts in developing resource conservation technologies like zero tillage, bed planting, reduced tillage etc. With the joint efforts of Directorate of Wheat Research and Rice-Wheat Consortium nearly two million hectares is under zero tillage and there are good prospects of its further spread to nearly 4 mha by 2001-12. More than 82% per cent of wheat area is under irrigated agriculture and keeping in view the impending scarcity of water it has become imperative to manage the irrigation water efficiently. Bed planting or raised beds, which is now catching up, saves nearly 40% of water and 20% nitrogen. From the nutrient point of view, the soil health is deteriorating and there is an urgent need to remove this fatigue by balanced use of fertilizers (integrated nutrient management). Other major constraints affecting wheat production are low rainfall under rainfed agriculture, terminal heat stress, salinity/alkalinity. The important biotic stresses are yellow and brown rusts and leaf blight while the insect pests like termites and aphids are to a lesser extent and season specific. There has been no rust epidemic since last three decades and the efforts made to mange the diseases and pests through IPM, gene deployment, increased host resistance against rusts, leaf blight, Karnal bunt, head scab and powdery mildew have helped in reducing losses and maximizing the returns to the farmers.

CIMMYT, Mexico has played an important role in strengthening the Indian wheat programme since the advent of Green Revolution. This support, primarily, was through germplasm exchange in form of international nurseries and trials and human resource development. However, in recent years the component of HRD has been greatly reduced to almost negligible extent. In light of the fresh MOU between CIMMYT and ICAR, emphasis is to be given to exchange of material with special reference to the climatic change, revitalize the HRD through visiting scientists' programme, developing collaborative research projects tackle the emerging challenges to wheat production. Modern tools like molecular breeding, functional genomics, deployment of trangenes for abiotic stresses etc., should get priority to maintain pace with time and growth.

India

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Table 1. Cultivars grown and released in irrigated and rainfed areas, 1955-present

(i) IRRIGATED AREAS

Period	Modern varieties (MV) hectares sown	Landraces hectares sown	Avg MV yield t/ha	Avg landrace yield t/ha	Cultivars released number	Dominant variety 1 hectares sown	Dominant variety 2 hectares sown	Avg farm size ha
1995-2005	22,752,000	0	2.83	NA	99	PBW 343	Lok1, HUW 234, UP 262	1.41
1985-1995	18,939,000	0	2.38	NA	77	HD 2329	HD 2285, Lok 1, UP 262, HUW 234	1.69
1975-1985	13,423,000	1,491,000	2.06	0.8	81	WL 711	HD 2009, Sonalika, WH 147	1.82
1965-1975	6,065,000	2,022,000	1.82	0.5	46	Kalyansona, Sonalika	K 68, Lerma Rojo	2.28
1955-1965	3,144,000	1,050,000	1.66	0.5	27	C 273	C 591, C 281, K 65	NA

(ii) RAINFED AREAS

Period	Modern varieties (MV) hectares sown	Landraces hectares sown	Avg MV yield t/ha	Avg landrace yield t/ha	Cultivars released number	Dominant variety 1 hectares sown	Dominant variety 2 hectares sown	Avg farm size ha
1995-2005	3,192,000	168,000	1.5	1	24	C 306	Lok1	
1985-1995	4,574,000	241,000	1.3	1	23	C 306	Lok 1, RAJ 1555 (d)	
1975-1985	5,534,000	1,384,000	0.8	0.5	22	C 306	K 68, NI 5439	
1965-1975	5,132,000	2,764,000	0.6	0.3	14	C 306	Bijyaga Yellow	
1955-1965	5,188,000	3,458,000	0.6	0.3		Same as irrigated	Same as irrgated	

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

(i) IRRIGATED AREAS

2 yr period	Conventional tillage hectares sown	Reduced/zero tillage kg/ha	Average N:P:K applied % of area	Fully mechanized hectares sown	Sown on flat hectares sown	Sown on raised beds ratio	Gravity:sprinkler irrigation mm or frequency	Irrigation applied
2004-2005	21,467,800	2,080,000	80:30:4	10%	same as conventional tillage	1,190	99.9:0.1	
2002-2003	21,799,200	736,000	78:28:3.8	8%		800	Same as above	
2000-2001	23,074,500	75,000	78:28:3.8	6%		500	Same as above	
1998-1999	23,448,400	3,500	75:27:3.5	5%		150	Same as above	
1996-1997	21,884,500	500	74:26:3.2	3%		50	Same as above	

(ii) RAINFED AREAS

2 yr period	Conventional tillage hectares sown	Reduced/zero tillage hectares sown	Average N:P:K applied kg/ha	Fully mechanized % of area	Annual cropping hectares sown	Cereal-fallow hectares sown	Weed control (grasses) methods	Broadleaf weeds methods
2004-2005	3,041,500	0	40:12:00	Negligible	_	Nil for wheat-fallow	Manual (90%) Isoproturon (10%)	Manual (75-80%), 2,4-D (20-25%)
2002-2003	3,044,000	0	38:10:00	Negligible	_	Nil for wheat-fallow	Manual (90%) Isoproturon (10%)	Manual (75-80%), 2,4-D (20-25%)
2000-2001	3,127,000	0	38:10:00	Negligible	_	Nil for wheat-fallow	Manual (90%) Isoproturon (10%)	Manual (75-80%), 2,4-D (20-25%)
1998-1999	3,657,000	0	36:09:00	Negligible	_	Nil for wheat-fallow	Manual (90%) Isoproturon (10%)	Manual (75-80%), 2,4-D (20-25%)
1996-1997	3,564,000	0	35:9:00	Negligible	_	Nil for wheat-fallow	Manual (90%) Isoproturon (10%)	Manual (75-80%), 2,4-D (20-25%)

Table 3 Current and emerging constraints to wheat production

Environmental constraint	YES/NO	Description of constraint	Area affected	Typical yield loss
Abiotic			**Hectares or % of total area**	**Range (%)**
Low rainfall	Yes	In rainfed or partially irrigated areas	5,000,000	10-50
Declining water resources (for irrigation)	Yes	Over-exploited ground water especially in Punjab, Haryana, Rajasthan, Western UP, Karnataka and Gujarat	15,000,000	10-20
Heat	Yes	High in eastern Gangetic plains, central and peninsular India; moderate in western Gangetic plains	20,000,000	10-30
Cold	No	Only in hills	Traces	Nil
Salinization	Yes	Due to sodic and saline soils	2,500,000	10-30
Soil physical degradation	Yes	In pockets	500,000	5
Micro-element deficiency (e.g., Zn, Bo)	Yes	Zinc deficiency is major factor while boron to a lesser extent in eastern and far-eastern parts	10,000,000-11,000,000	5
Micro-element toxicity (e.g., Al, Bo)	No	In traces in northeastern states	0	0
Lodging	No	Sporadic - occurs especially due to windy conditions immediately after irrigation	1,000,000	5-10
Other				
Biotic				
Diseases				5-15
Leaf rust	No	Prevalent in all the parts of the country, however, varieties grown are resistant	Negligible	NA
Yellow rust	No	More prevalent in hills and northwestern parts of the country. Varieties grown are resistant	Negligible	NA
Leaf blight	Yes	More prevalent in north eastern plains followed by peninsular, central and low in northwestern parts	15,000,000	5
Pests	Yes	Higher incidence of termites is observed in northwestern plains	5,000,000	5-10
Aphids	No	Incidence of aphids is sporadic	2,000,000	1-2
Weeds				
	Yes	Grassy - Phalaris minor, wild oat Broad- Chenopodium, Rumex sp., Medicago sp. Phalaris minor is more prevalent in rice-wheat system as well as irrigated cotton wheat system occupying 9m ha. Other broadleaved weeds are also problem in rainfed area	9,000,000 - P. minor	15-20
Socioeconomic constraint				
Credit	Yes	Timely availability in sufficient quantity is all that is required. In its absence, all operations get affected including input usage. Small and marginal farmers are most affected (70%)	100%	Estimates not available
Seed availability/quality	Yes	Most critical input. Its timely availability and quality is all responsible for the potential yields.	16,000,000	
Fertilizer availability	Yes	Its availability in required quantity and at initial and growth stage, is critical. It affects the yield to a great extent. The problem is more in Punjab, Haryana and irrigated areas of Maharashtra.	6,000,000	
Fungicide/pesticides/herbicides availability/cost	No	More important is herbicide which is expensive	6,000,000	
Mechanization/access to suitable machinery	No	Inavailability of suitable machinery for the specific purpose can reduce the yield to a certain extent. It is the problem of small and marginal farmers.	6,000,000	
Labor	No	Labor requirement at harvesting/threshing stage is at peak. Its shortage here can reduce yields to a small extent in the form of losses.	5,500,000	
Transport	Yes	For transporting the farm produce to local market.	5,500,000	
Grain price/ marketing	No	The maximum support price offered for wheat by the government encourages the farmers to grow wheat	NA	
Conflict with other crop or livestock systems	No	Initiation of diversification of rice wheat system, especially in northwestern plains	5,500,000	

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	YES/NO	Description of constraint	Priority (Highest, high, moderate, low, not)	Approx investment required $
Field station operations (budget, land, staff, etc.)	Yes	Increased investments in funds for trials as well as field staff is important. Land, in general is not a constraint	Highest	725,000
Field machinery	Yes	Availability of tractor, seed drills and threshers is a limitation at some research stations	High	1,200,000
Technical assistance staff	No	Technical staff is lacking at some centers, especially under State Agricultural Universities	Moderate	500,000
Scientific expertise (genetics, pathology, agronomy, etc.)	No	Scientific expertise is adequate	Not	NA
Socioeconomic expertise (market & impacts analysis, etc.)	No	Specialized and trained personnel are required	Moderate	200,000
Labs/instruments (e.g., quality LAB, MAS, dryers, etc.)	Yes	Specialized labs and upgrading of biotechnology labs	High	500,000/5 years
Computers/software/GIS	No	Few centers may not be having access to computers	Low	150,000
Controlled growth environments	Yes	Glasshouses required for studies on heat and drought tolerance as well as for transgenic, doubled haploids, etc.	High	2,300,000
Access to genetic resources/storage	Yes	Access to genetic resources is a low constraint, but storage modules are more important	Moderate	1,200,000
Training resources (classrooms, etc.)	Yes	Advance training is required	High	500,000
Transport	Yes	Shortage of vehicles for monitoring of wheat trials	High	600,000
Resources to support collaboration & information sharing Other	Yes	Collaborations within and outside the country	High	2,250,000

Table 5. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance 1-6*	Example of partnership Optional
Farmer groups	1	Farmers associations, Farmers Clubs, Village Panchayat, etc.
Local private companies	3	Farm machinery, seed, agro-chemical food processing companies, etc.
International centers	1	CIMMYT, ICARDA, IPGR, FAO, USDA, ACIAR, etc.
Foreign research institutions	2	Swiss-ISCB, INRA-France, UC-Davis, Cornell University, etc.
Multinationals	4	MNC related to seeds, agro-chemicals, food processing, biotech, etc.
NGOs	3	Lok Bharti, Gramin Vikas Trust, etc.

*Ranking (1=most important, 6=least important)

Table 6. Most useful /desirable outputs from CGIAR centers

CIMMYT output	Specify	Priority
Germplasm		
Advanced lines with generic traits (yield, disease res., etc.)	Advanced lines for high yield, resistance and quality	High
Segregating bulks (F2 onwards)	NIL	Not
Genetic resources	Genetics stocks for biotic and abiotic stresses and quality traits	Moderate
Training/knowledge sharing		
Basic training for younger scientists	Younger scientists are well trained in basics during their post graduation studies	Low
Advanced courses for mid-career scientists	Advanced courses required regarding emerging tools - e.g., biotechnology, transgenic and specialized screening techniques	Highest
Specialized visits of individual scientists, e.g., to CIMMYT	For international exposure	Highest
Visits of CIMMYT scientists to your program	Knowledge sharing for specific issues	High
Methodologies/Information/Publications on		
Breeding (e.g., international nursery reports; IWIS, etc.)	Yes, Reports	Low
Pathology and pest control	Emerging global issues and tools	Low
Genetics (quantitative and molecular)	Emerging global issues and tools	Moderate
Pre-breeding and genetic resources	Emerging global issues and tools	High
Physiology (crop and/or cellular)	Emerging global issues and tools	Moderate
Statistics and experimental design	Nil	Not
Crop management	Emerging global issues and tools	Moderate
Participatory methods	Emerging global issues and tools	High
Seed technolgy	New technologies and methodologies and seed priming	Moderate
Social science and economic analysis	Emerging global issues and tools	Low
Training methods	Nil	Not
Software support for databases, GIS, websites, etc.	Specialized software for data base and analysis	Moderate

Wheat Production and Research in Iran: A Success Story

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About 6.5 million hectares are grown to wheat in Iran: 2.5 million ha are irrigated and 4.0 million ha grow under rainfed conditions. In 2003 - 2004 cropping season, the total production reached 14.6 million tons: 67% was produced in irrigated crop (average 3,827 Kg/ha) and 33% was produced in dryland conditions (average 1,187 Kg/ha).

The rainfed areas are divided in cold (60%), temperate (10%) and warmer areas (30%).
Irrigated wheat (95% improved cultivars) is grown in four different mega agro-ecological zones characterized as follows:

Zone I (Northern Warm and Humid Zone): 8% or 204,000 ha
Warm temperatures, high rainfall, humid conditions; altitude below 800 masl.
Average absolute min. temp. is –6ºC; less than 30 freezing days.
Spring wheat cultivars.
Caspian sea shore (Mazandaran, Golestan, Moghan plains, and Gilan province)
Zone II (Southern Warm and Dry Zone): 27.2% or 693,000 ha
Warm temperatures, low rainfall; altitude below 500 masl.
Average absolute min. temp. is –5ºC; about 15 freezing days.
Spring wheat cultivars.
Persian Gulf and Oman Sea coastal areas
(Khoozestan, Booshehre, Hormozgan, Sistan and Baluchestan, Ilam, and some parts of Yazd, Kerman, Lorstan and Fars Provinces)
Zone III (Temperate Zone): 30.7% or 781,000 ha
Temperate temperatures, Moderate rainfall; altitude around 1000 masl.
Average absolute temp. is –10 ºC ; about 50 freezing days.
Spring and Facultative wheat cultivars.
Isfahan, Yazd, Kerman, Markazi province, Central parts of Khorasan and Fars, and some parts of Lorestan and Kermanshah provinces, Varamin and Karadj regions
Zone IV (Cold Zone): 34.1% or 870,000ha
Cold to very cold temperatures, low to moderate rainfall; altitude above 1000 masl
Average absolute min. temp. is –14 ºC, about 3 months freezing days.
Winter and/or cold tolerant facultative wheat cultivars
Hamedan, Ardabil, East and West Azarbaijan, Zanjan, Qazvin, Chehar Mohal Bakhtiari, and some parts of Khorasan, Fars provinces.

Breeding objectives include:
-High genetic potential, yield stability, wide and specific adaptation with desirable agronomic traits
-Resistance to biotic stresses such as rusts (YR, LR & SR), Fusarium , Septoria, Powdery mildew, bunts, smuts, etc.
-Tolerant to abiotic stresses such as cold, heat, drought, salinity and pre-harvest sprouting, etc.
-High quality for traditional flat bread baking
-High quality in durum wheat for macaroni industries
-Dual Purpose barley and triticale
-Agronomic and wheat crop management packages
-Breeder and foundation seeds multiplication

During the 1978 – 2003 period, 26 wheat cultivars with CIMMYT origin have been selected and released. In 2004-2005 cropping season, 46 improved bread wheat and durum wheat cultivars 44.4% of which are of CIMMYT origin were grown in the different irrigated agro-ecological zones. Chamran (Attila 50Y) is widely grown (25% of certified seed planned to be supplied to farmers). Two recently released durum wheat cultivars: Arya and Karkheh (with CIMMYT origin) also comprise 54% of certified seed planned to be supplied to the farmers. The Seed and Plant Improvement Institute (SPII) remains the main scientific and technical supporter of this national plan.

Iran

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Table 1. Cultivars grown and released in irrigated and rainfed areas, 1955-present

(i) IRRIGATED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	2,060,000	240,000	4.5	2.2	18	Chamran	Alvand	
1985-1995	2,000,000	200,000	3.7	2.2	16	Ghods and Falat	Tajan	
1975-1985	885,000	1,000,000	2.3	1.2	11	Roshan and Omid	Azadi and Golestan	
1965-1975	500,000	1,000,000	1.8	1	8	Roshan and Omid	Arvand1 and Moghan1	
1955-1965								

(ii) RAINFED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	1,400,000	2,500,000	1.5	0.8	8	Sardari	Azar2 and Zagros	
1985-1995	500,000	3,783,000	1.2	0.78	1	Sardari	Sabalan and Bistoon	
1975-1985		3,976,000		0.61	2	Sardari	Sabalan and Bistoon	
1965-1975		,		0.44	1	Sardari	Local varieties	
1955-1965								

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

(i) IRRIGATED AREAS

2 yr period	Conventional tillage *hectares sown*	Reduced/zero tillage *hectares sown*	Average N:P:K applied *kg/ha*	Fully mechanized *% of area*	Sown on flat *hectares sown*	Sown on raised beds *hectares sown*	Gravity:sprinkler irrigation *ratio*	Irrigation applied *mm or frequency*
2004-2005	2,400,000	0	120:90:60	55	840,000	1,560,000	0.17	500 - 800 mm
2002-2003	2,398,606	0	120:90:60	50	959,442	1,439,200	0.15	500 - 800 mm
2000-2001	2,293,839	0	120:90:60	50	1,081,032	1,261,600	0.05	500 - 800 mm
1998-1999	2,177,901	0	120:90:60	45	1,023,613	1,154,290	0.03	500 - 800 mm
1996-1997	2,162,064	0	120:90:60	42	1,081,032	1,081,030	0.015	500 - 800 mm

(ii) RAINFED AREAS

2 yr period	Conventional tillage *hectares sown*	Reduced/zero tillage *hectares sown*	Average N:P:K applied *kg/ha*	Fully mechanized *% of area*	Annual cropping *hectares sown*	Cereal fallow *hectares sown*	Weed control *methods*	Broad leaf *weeds*
2004-2005	3,900,000	0	50:30:30	45	1,900,000	2,000,000	Herbicide	Herbicide
2002-2003	4,010,802	0	50:30:30	40	2,010,802	2,000,000	Herbicide	Herbicide
2000-2001	3,947,002	0	50:30:30	35	1,847,002	2,100,000	Herbicide	Herbicide
1998-1999	3,375,231	0	50:30:30	35	875,231	2,500,000	Herbicide	Herbicide
1996-1997	2,938,653	0	50:30:30	30	438,231	2,500,000	Herbicide	Herbicide

Table 3. Current and emerging constraints to wheat production

Environmental constraint Abiotic	YES/NO	Description of constraint	Area affected % of total area	Typical yield loss range (%)
Low rainfall	Yes	Low rainfall with untimely distribution causes crop to suffer from water deficit	75	5-100
Declining water resources (for irrigation)	Yes	Irrigation frequency is reduced in competition with cash crops	35	5-60
Heat	Yes	Terminal heat during anthesis and grain filling period causes crop loss in southern part of the country	10	5-40
Cold	Yes	Frost in winter and late frost in early spring cause damage to wheat in cold mountainous and cold temperate regions	40	5-40
Salinization	Yes	Saline soils and water are major limtations to wheat production in Soth and central part of the country	10	5-30
Soil physical degradation	Yes	Improper tillage and fallow cause physical degradation of soil in arid and semiarid areas	>70	NA
Micro-element deficiency (e.g., Zn, Bo)	Yes		>50	NA
Micro-element toxicity (e.g., Al, Bo)	No		>75	NA
Lodging	Yes		NA	5-10
Other				
Biotic				
Diseases	Yes	Yellow Rust, Fusarium head blight, smuts and bunts in Caspian Region, and western part of the country, respectively	40	5-20
Pests	Yes	Sunni bug , Russian aphid, thrips and Sawfly	30	5-40
Weeds	Yes	Wild rye, wild oats, Bromus, Hordeum spontaneum and Malva spp. Brassica spp.,	90	5-60
Socioeconomic constraint				
Credit				
Seed availability/quality	Yes	In irrigated systems, about 51% of required certified seed and in rainfed system about 20% of required certified seed are provided in each cropping season by a semi-governmental company		
Fertilizer availability	Yes	Required fertilizer is supplied by semi-governmental company, however, it might not be in time		
Fungicide/pesticides/herbicides availability/cost	Yes	It is supplied, however the quality of chemicals in recent years is under question		
Mechanization/ access to suitable machinery	Yes	Mechanization is one of the major constraints in wheat production, because there is not sufficient machinery supplied and what is supplied is most frequently not suitable for either system (irrigated and rainfed)		
Labor	Yes	The cost of labor is too high, and farm labor is not trained and skilled for the given jobs. Since many people from agricultural areas have emigrated to the big cities, this constraint would appear serious		
Transport	Yes	Suitable transport and roads are also constraints to wheat production		
Grain price/ marketing	Yes	Wheat is purchased by the governmental system with a guaranteed price, however, wheat is not purchased based on its quality, e.g., Protein, hectoliter weight and grain hardness etc.		
Conflict with other crop or livestock systems	Yes	There are conflicts with summer crops, in particular cash crops, in terms of water allocation and timely sowing and harvesting		

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	YES/NO	Description of constraint	Priority *(Highest, high, moderate, low, not)*	Approx *investment required $*
Field station operations (budget, land, staff etc.)	Yes	Budget	Highest	
Field machinery	Yes	Most of the available field machinery is too old and its efficiency and accuracy has decreased dramatically	High	
Technical assistance staff	Yes	This is raising as a critical issue in all research program	Highest	
Scientific expertise (genetics, pathology, agronomy, etc.)	Yes	To staff the required disciplines we need to recruit scientists in genetics (biotechnology), quality, agronomy and breeding),	High	
Socioeconomic expertise (market & impacts analysis, etc.)	Yes	This area is the neglected area in our research and must be strengthened	High	
Labs/instruments (e.g., quality LAB, MAS, dryers, etc.)	Yes	There are labs but they must be completed by purchasing suitable and necessary instruments and equipment	High	
Computers/software/GIS	Yes	Needs to computer facilities should be met, however access to advanced software is necessary	High	
Controlled growth environments	Yes	Controlled growth environments are available, but need to be expanded	Moderate	
Access to genetic resources/storage	Yes	For doing quality breeding/genetics research, having right genetic stocks and equipment are necessary	High	
Training resources (classrooms, etc.)	No	It is available		
Transport	Yes	Transportation is vital. Most of the vehicles are old and not efficient	High	
Resources to support collaboration & information sharing	Yes	Information sharing is very important, but we are not very good at it	High	
Other				

Table 5. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance *1-6**	Example of partnership *Optional*
Farmer groups	4	Participatory variety selection, and registered and certified seed multiplication
Local private companies	4	Registered and certified seed multiplication
International centers	3	Germplasm and education
Foreign research institutions	5	Germplasm
Multinationals	_	None
NGOs		None so far

*Ranking (1=most important, 6=least important)

Table 6. Most useful /desirable outputs from CGIAR Centres

CIMMYT Output	Specify	Priority *(Highest, high, moderate, low, not)*
Germplasm		
Advanced lines with generic traits (yield, disease res., etc.)	High yielding, resistance to abiotic (terminal drought, terminal heat, cold/frost and salinity) and biotic (YR, LR, SR, FHB, PM, Septoria and Tan Spot) stresses, bread making quality, semolina quality	Highest
Segregating bulks (F2 onwards)	Genetically fixed lines are preferred	Moderate
Genetic resources	Right genetic materials are essential to genetics and physiological studies	Highest
Training/knowledge sharing		**Moderate**
Basic training for younger scientists	Since most of our young researchers are MSc and PhD, little basic training is provided	Moderate
Advanced courses for mid-career scientists	Breeding for drought, salinity, heat, cold, high yield potential as well as agronomy, pathology, physiology, quality, and biotechnology courses are required	Highest
Specialized visits of individual scientists, e.g., to CIMMYT	This is very important to our research program	Highest
Visits of CIMMYT scientists to your program	This is also very important to our research program	Highest
Methodologies/Information/Publications on		**High**
Breeding (e.g., international nursery reports; IWIS, etc.)	Methodologies/information and publications in these areas would improve and strengthen our foundation for future activities	High
Pathology and pest control	" " " " " " "	High
Genetics (quantitative and molecular)	" " " " " " "	High
Pre-breeding and genetic resources	" " " " " " "	High
Physiology (crop and/or cellular)	" " " " " " "	High
Statistics and experimental design	" " " " " " "	High
Crop management	" " " " " " "	High
Participatory methods	" " " " " " "	High
Seed technolgy	" " " " " " "	High
Social science and economic analysis	" " " " " " "	High
Training methods	" " " " " " "	High
Software support for databases, GIS, websites, etc.	" " " " " " "	High

Kazakhstan

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Table 1. Cultivars grown and released in irrigated and rainfed areas, 1955-present

(i) IRRIGATED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	1,260,000	0	1.41	0	16	Steklov.-24	Progress	600
1985-1995	1,060,000	0	1.32	0				250
1975-1985	1,120,000	0	1.15	0				
1965-1975	…..	0	1	0				
1955-1965	……	0	0.62	0				

(ii) RAINFED AREAS

Period	Modern varieties (MV) *hectares sown*	Avg MV yield *t/ha* Northern Kazakhstan	Southern Kazakhstan	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha* Northern Kazakhstan	Southern Kazakhstan
1995-2005	11,200,000	0.8	1.3	0	5-8	5,500,000	2,000,000	15,000	1,000
1985-1995	13,200,000	0.8	0.85	0	5-8	7,500,000	2,500,000	20,000	1,000
1975-1985	14,200,000	1.0	1.0	0	5-8	8,000,000	2,000,000	40,000	
1965-1975	13,100,000	0.7	0.96	0	5-8	7,500,000	2,000,000	40,000	
1955-1965	12,600,000	0.6	0.84	0	5-8	5,000,000	2,500,000	40,000	

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

(ii) RAINFED AREAS

2 yr period	Conventional tillage *hectares sown*	reduce/zero tillage *hectares sown*	Average N:P:K aplied *kg/ha*	fully mechanized *% of area*	Annual cropping	Cereal Fallow	Weed control (grasses)	Broad *(*Leaf weeds)
2004-2005	11,000,000	100,000	3-5	100	7,500,000	3,000,000	Mechanical-chemnical	Chemical (2,4-D)
2002-2003	11,000,000	50,000	3-4	100	7,500,000	2,500,000	Mechanical-chemnical	Chemical
2000-2001	10,400,000	50	1-2	100	8,900,000	2,000,000	Mechanical-chemnical	Chemical
1998-1999	10,000,000	0	1-2	100	8,900,000	2,000,000	Mechanical-chemnical	Chemical
1996-1997	12,000,000	0	1-2	100	8,900,000	2,500,000	Mechanical-chemnical	Chemical

Table 3a. Northern Kazakhstan. Current and emerging constraints to wheat production

Environmental constraint	YES/NO	Description of constraint	Area affected	Typical yield loss
Abiotic			*hectares or % of total area*	*range (%)*
Low rainfall	Yes		100	up to 70%
Declining water resources (for irrigation)				
Heat	Yes		100	up to 50%
Cold	Yes		100	up to 50%
Salinization	Yes		50	up to 30%
Soil physical degradation	Yes		100	up to 30%
Micro-element deficiency (e.g., Zn, Bo)	Yes		50	up to 15%
Micro-element toxicity (e.g., Al, Bo)	No			
Lodging	Yes		100	up to 30%
Other				
Biotic				
Diseases	Yes	Septoriosis, Helminthosporiosis, Brown rust	100	up to 50%
Pests	Yes	Hessian fly	90	up to 50%
Weeds	Yes	Wild oat, Knotweed, Sow-thistle	100	up to 50%
Socioeconomic constraint				
Credit	Yes			
Seed availability/quality	Yes			
Fertilizer availability	Yes			
Fungicide/pesticides/herbicides availability/cost	Yes			
Mechanization/access to suitable machinary	Yes			
Labor	No			
Transport	Yes			
Grain price/ marketing	Yes			
Conflict with other crop or livestock systems	No			

Table 3b. Southern Kazakhstan. Current and emerging constraints to wheat production

Environmental constraint Abiotic	YES/NO	Description of constraint	Area affected hectares or % of total area	Typical yield loss range (%)
Low rainfall	Yes	Insufficient precipitation - 200-300mm	60%	50%
Declining water resources (for irrigation)	Yes			
		Heat stress (high temperatures) reduces wheat production	60%	15-45%
Heat	Yes	Drought and dry wind at the stage of tillering-ripeness.		
Cold	Yes	Low winter hardiness leads to low levels of cold survival in some years	10%	13-25%
Salinization	Yes	Salinity damage of wheat is caused both by sodium and chloride ions.	20%	25-30%
Soil physical degradation	Yes	Soil compression, degradation of structure	70%	15-20%
Micro-element deficiency (e.g., Zn, Bo)	No			
Micro-element toxicity (e.g., Al, Bo)	No			
Lodging	Yes	Lodging of tall cultivars - Steklovidnaya-24, Karlygash		
Other				
Biotic				
Diseases (specify 3 most important diseases)	Yes	Yellow rust (Puccinia striiformis West.)	1.5 million ha	20-75%
		Leaf rust (Puccinia recondita Desm.)	10 millon. ha	30-40%
		Smut (Tilletia caries DC. Tul.)	133,000 ha	20-30%
Pests (specify most important)		Tartle (Eurygaster integriceps Put.)	4.8 million ha	30-40%
		Granary weevil (Sitophilus granarius)	1 million ha	15-20%
Weeds		Field pea (Pisum arvense)	1.5 million ha	13-15%
(specify 3 most important grass and broadleaf weeds)		Black bindweed (Polygonum convulvus)	3.5 million ha	14-17%
		Field sow thistle (Sonchus arvensis)	4.5 million ha	13-15%

Table 4a. Northern Kazakhstan. Current and emerging constraints to wheat improvement activities

Constraint	YES/NO	Description of constraint	Priority *(Highest, high, moderate, low, not)*	Approx investment required $
Field station operations (budget, land, staff, etc.)	Yes		High	500,000
Field machinery	Yes		High	500,000
Technical assistance staff	Yes		High	100,000
Scientific expertise (genetics, pathology, agronomy, etc.)	Yes		Highest	200,000
Socioeconomic expertise (market & impacts analysis, etc.)	Yes		High	100,000
Labs/instruments (e.g., quality LAB, MAS, driyers, etc.)	Yes		High	500,000
Computers/software/GIS Yes High 500,000				
Controlled growth environments	Yes		High	500,000
Access to genetic resources/storage	Yes		High	100,000
Training resources (classrooms, etc.)	Yes		High	100,000
Transport	Yes		High	100,000
Resources to support collaboration & information sharing	Yes		High	200,000
Other				

Table 4b. Southern Kazakhstan. Current and emerging constraints to wheat improvement activities

Constraint	YES/NO	Description of constraint	Priority	Approx investment required $
Field station operations (budget, land, staff etc.)				
Field machinery				
Technical assistance staff	Yes		High	5,000
Scientific expertise (genetics, pathology, agronomy, etc.)	No			
Socioeconomic expertise (market & impacts analysis, etc.)				
Labs/instruments (e.g., quality LAB, MAS, dryers, etc.)	Yes	Insufficient of modern equipment chemicals	Highest	8,000
Computers/software/GIS	Yes	We need modern software for statistics	Moderate	2,000
Controlled growth environments	Yes	Absence of modern climatic chambers	High	5,000
Access to genetic resources/storage	Yes	Absence of conditions for storage	High	5,000
Training resources (classrooms, etc.)	Yes		Moderate	3,000
Transport	Yes	Transport for research in different environments	Highest	4,000
Resources to support collaboration & information sharing	Yes	Workshop & master-class for scientists	Highest	3,000
Other				

Table 5a. Northern Kazakhstan. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance *1-6**	Example of partnership *Optional*
Farmer groups	1	On-farm trials, participatory research, etc.
Local private companies	3	Joint technical projects
International centers	2	Joint research projects, programs, etc.
Foreign research institutions	4	
Multinationals	6	
NGOs	5	

* Ranking (1=most important, 6=least important)

Table 5b. Southern Kazakhstan. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance 1-6*	Example of partnership Optional
Farmer groups	4	
Local private companies	6	
International centers	1	
Foreign research institutions	2	
Multinationals	3	
NGOs	5	

* Ranking (1=most important, 6=least important)

Table 6a. Northern Kazakhstan. Most useful /desirable outputs from CGIAR centers

CIMMYT Output	Specify	Priority *(Highest, high, moderate, low, not)*
Germplasm		
Advanced lines with generic traits (yield, disease res., etc.)	Yield, resistance to biotic and abiotic stresses, grain quality	Highest
Segregating bulks (F2 onwards)		High
Genetic resources		High
Training/knowledge sharing		
Basic training for younger scientists	Breeding, agronomy, biotechnology	High
Advanced courses for mid-career scientists	Breeding/genetics, agronomy, pathology, physiology, biotechnology	High
Specialized visits of individual scientists, e.g., to CIMMYT		High
Visits of CIMMYT scientists to your program		High
Methodologies/Information/Publications on		
Breeding (e.g., international nursery reports; IWIS, etc.)		High
Pathology and pest control		High
Genetics (quantitative and molecular)		High
Pre-breeding and genetic resources		High
Physiology (crop and/or cellular)		High
Statistics and experimental design		High
Crop management		High
Participatory methods		High
Seed technolgy		High
Social science and economic analysis		High
Training methods		High
Software support for databases, GIS, websites, etc.		High

Table 6b. Southern Kazakhstan. Most useful /desirable outputs from CGIAR centers

CIMMYT Output	Specify	Priority
Germplasm		
Advanced lines with generic traits (yield, disease res., etc.)	Disease resistance	Highest
Segregating bulks (F2 onwards)		High
Genetic resources	Wild relatives	Moderate
Training/knowledge sharing		
Basic training for younger scientists	Genetic wheat improvement	High
Advanced courses for mid-career scientists	Plant breeding and MAS-selection	Highest
Specialized visits of individual scientists, e.g., to CIMMYT	Collaborative research	High
Visits of CIMMYT scientists to your program	Workshops, lectures	Moderate
Methodologies/Information/Publications on		
Breeding (e.g., international nursery reports; IWIS, etc.)		High
Pathology and pest control		High
Genetics (quantitative and molecular)		Highest
Pre-breeding and genetic resources		Moderate
Physiology (crop and/or cellular)		Low
Statistics and experimental design		Moderate
Crop management		High
Participatory methods		Moderate
Seed technology		High
Social science and economic analysis		Moderate
Training methods		High
Software support for databases, GIS, websites, etc.		High

Kyrgyzstan

M. Djunusova

Table 1 Cultivars grown and released in irrigated and rainfed areas, 1955-present

(i) IRRIGATED AREAS

	Modern varieties (MV)	Landraces	Avg MV yield	Avg landrace yield	Cultivars released	Dominant Variety 1	Dominant Variety 2	AvgFarm Size
Period	*hectares sown*	*hectares sown*	*t/ha*	*t/ha*	*number*	*hectares sown*	*hectartes sown*	*ha*
1995-2005	320,000		6-12 t/h		27	Intensivnaya	Bezostaya1	
1985-1995	286,000				7	Intensivnaya		
1975-1985					4	Bezostaya1		
1965-1975					1	Bezostaya1		
1955-1965								

(ii) RAINFED AREAS

	Modern varieties (MV)	Landraces	Avg MV yield	Avg landrace yield	Cultivars released	Dominant Variety 1	Dominant Variety 2	Avg Farm Size
Period	*hectares sown*	*hectares sown*	*t/ha*	*t/ha*	*number*	*hectares sown*	*hectartes sown*	*ha*
1995-2005	198,000		2-5t/ha		3	Adyr, Erythr.760		
1985-1995					1	Erythr.13		
1975-1985					1	Frunzenskaya60		
1965-1975								
1955-1965								

Table 3. Current and Emerging Constraints to Wheat Production

Environmental Constraint	YES/NO	Description of constraint	Area Affected	Typical Yield Loss
abiotic			**hectares or % of total area**	**range (%)**
Low rainfall	yes	50-250 mm per one year - non-supplied rainfed, 250-500mm per one year - supplied rainfed	40%	50%
Declining water resources (for irrigation)				
Heat				
Cold				
Salinization	yes	The salinizated area of Republic is 1 mln ha.	6.40%	10-80%
Soil physical degradation				
Micro-element deficiency (eg Zn, Bo)		Non studied. Need to study.		
Micro-element toxicity (eg Al, Bo)		Non studied. Need to study.		
Lodging	yes	Absence of sustainable commercial varieties to lodging		
Other				
biotic				
Diseases	yes	YR, Tilletia tritici, Septoria		
Pests	yes	Cereal leaf beetle, Sun-pest		
Weeds	yes	Sonchus, Sind-weed, Avena fatua		
Socio-Economic Constraint				
Credit	yes	High percent of tax		
Seed availability/quality	yes	Non certificated seed sale		
Fertilizer availability	yes	Prices are high		
Fungicide/pesticides/herbicides availability/cost	yes	Prices are high		
Mechaniztaion/ access to suitable machinary	yes	Deficiency of seed-sowing and harvesting machinery		
Labour	yes	Salary is low		
Transport	yes	Deficiency and high price of petrol		
Grain price/ marketing	yes	High price of seed material and non systemized marketing		
Conflict with other crop or livestock systems	no			

Table 4. Current and Emerging Constraints to Wheat Improvement Activities

Constraint	YES/NO	Description of constraint	**Priority** *(Highest, high, moderate, low, not)*	**Approx investment required** *$*
Field station operations (budget, land, staff etc.)	yes	Deficiency of arable land, non sufficient of budget and high qualificated staff.	high	
Field machinery	yes	Deficiency of seed-sowing and harvesting machinery	high	
Technical assistance staff	yes	Salary is low	moderate	
Scientific expertize (genetics, pathology, agronomy etc)	yes	Deficiency of high qualificated scientists and laboratory equipments	high	
Socio-economic expertize (market & impacts analysis etc)	yes			
Labs/instruments (eg quality LAB, MAS, driers, etc.)	yes	Deficiency of budget	high	
Computers/software/GIS	yes			
Controlled growth environments	yes			
Access to genetic resources/storage	no	Thanks to support of International Centers (CIMMYT,ICARDA)		
Training resources (classrooms etc)	yes			
Transport	yes			
Resources to support collaboration & information sharing	no			
Other				

Table 5. Relative Importance of Research Partnerships to Achieving National Wheat Program Goals

Collaborative Partners	Importance *1-6**	Example of Partnership *optional*
Farmer groups	1	
Local Private Companies	1	
International Centers	1	
Foreign Research Inst	1	
Multinationals	1	
NGOs	1	

* Ranking (1=most important, 6=least important)

Table 6. Most useful /desirable outputs from CGIAR Centres

CIMMYT Output	Specifiy	**Priority** *(Highest, high, moderate, low, not)*
Germplasm		**highest**
Advanced lines with generic traits (yield, disease res. etc)	**AYT, Rust, septoria nursery**	**high**
Segregating bulks (F2 onwards)	**F3 segregation population**	**moderate**
Genetic Resources		
Training/knowledge sharing		
Basic training for younger scientists	**long training-course**	**high**
Advanced courses for mid carear scientists		
Specialized visits of individual scientists eg to CIMMYT	**short training-course**	**highest**
Visits of CIMMYT scientists to your program	**joint programms**	**highest**
Methodologies/Information/Publications on		
Breeding (eg international nursery reports; IWIS etc)	**FAWWON, WWONIR, WWONSA**	**highest**
Pathology and pest control	CWAR-TN, Septoria, Sun pest, cereal Leaf Beat	highest
Genetics (quantitative and molecular)		
Pre-breeding and genetic resources		
Physiology (crop and/or cellular)		
Statistics and experimental design		highest
Crop management		
Participatory methods		
Seed technolgy		high
Social science and economic analysis		
Training methods		
Software support for databases, GIS, websites, etc		high

Wheat Production in Mexico

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Wheat was introduced to Mexico by the Spaniards around the 1500. Most landraces were grown either under stored moisture or rainfed areas. By 1940 most landraces were highly susceptible to stem rust. Further introductions from Australia, Canada and the United States, alleviated temporarily the consecutive stem rust epidemics until the first resistant variety to Stem rust was release in 1950. Landraces were cultivated until 1965 in larger areas. In the period of 1992 to1994, CIMMYT-INIFAP came together to collected most of the remained landraces cultivated in small patches in many Mexican states. Today, very few introductions remain under cultivation, since modern varieties have almost completely replaced the landrace cultivars. Among the agronomic practices in the Irrigated areas, undoubtedly the use of raised beds, designed originally for weed control has been the most remarkable contribution from Mexican scientist of INIFAP at Sonora and currently followed by CIMMYT scientists and promoted in many areas of the world. Mexican wheat production areas are located under two contrasting systems, the Irrigated grown during Winter-Spring season and the rainfed system where wheat grows during Summer to Fall period. Since in the irrigated areas, water is becoming scarcy, drought tolerance must be a principal characteristic of the modern varieties. However, for the rainfed areas of Mexico, not only drought tolerance but earliness is required, since early frost is common. After the successful control of the stem rust, modern varieties must have the durable type of resistance to leaf and stripe rust. Many wheat varieties have been released in Mexico (from Yaqui 50 to Gema C2005) as result of the very close cooperation and partnership between INIFAP and CIMMYT. International Nurseries such as the ESWYT, IBWSN, EDYT and the IDWSN, have been the source of germplasm for the National Wheat Breeding Program from where new advanced wheat lines have been identified and released (i.e.Palmerin F2004, Rajaram F2004, Kronstand F2004, Samayoa C2004, Banamichi C2004, Bataques C2004 y Gema C2005 just to cite the most recent). New advanced lines with high yield potential and good industrial quality, with durable type of rust resistance for irrigated as well as drought tolerance and early germplasm for rainfed areas will be required from CIMMYT to contribute to the INIFAP efforts to assure the sustainability of wheat production in Mexico.

Mexico

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Table 1. Cultivars grown and released in irrigated and rainfed areas, 1955-present

(i) IRRIGATED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha**	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	562,000	0	4.92		Diverse	Altar	Rayón	
1985-1995	783,000	0	4.61		Diverse	Seri	Rayón	
1975-1985	785,000	0	4.32		Diverse	Jupateco	Salamanca	
1965-1975	606,000	85,000	3.21		Diverse	Siete Cerros	Lerma Rojo	
1955-1965	377,000	340,000	1.65		Diverse	Many		

* = Rendimiento comercial medio por ha que considera MV y Landrace

(ii) RAINFED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha***	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	138,000	5,000	1.92		Diverse	Temporalera	Romoga	
1985-1995	196,000	7,000	1.85		Diverse	Zacatecas	Pavon	
1975-1985	134,000	10,000	1.38		Diverse	Zacatecas	Lerma Rojo	
1965-1975	26,000	42,000	1.24		Diverse	Diverse	-	
1955-1965	9,000	126,000	1.09		Diverse	Diverse	-	

** = Rendimiento medio comercial por ha considera MV y Landrace

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

(i) IRRIGATED AREAS

2 yr period	Conventional tillage *hectares sown*	Reduced/zero tillage *hectares sown*	Average N:P:K applied *kg/ha*	Fully mechanized *% of area*	Sown on flat *hectares sown*	Sown on raised beds *hectares sown*	Gravity:sprinkler irrigation *ratio*	Irrigation applied *mm or frequency*
2004-2005	NA		250:35:00	100	NA	NA	1:00	4-5 irrigations
2002-2003	626,648		250:35:00	100	275,633	351,015	1:00	4-5 irrigations
2000-2001	1,093,163		250:35:00	100	574,079	519,084	1:00	4-5 irrigations
1998-1999	889,432		250:35:00	100	649,900	239,532	1:00	4-5 irrigations
1996-1997	1,040,858 (Wheat)		250:35:00	100	814,861	224,997	1:00	4-5 irrigations

(ii) RAINFED AREAS

2 yr period	Conventional tillage *hectares sown*	Reduced/zero tillage *hectares sown*	Average N:P:K applied *kg/ha*	Fully mechanized *% of area*	Annual cropping *hectares sown*	Cereal-fallow *hectares sown*	Weed control (grasses) *methods*	Broadleaf weeds *methods*
2004-2005	NA						Mechanical prior to seeding	Chemical
2002-2003	161,593	0	80:40:20	100			"	Chemical
2000-2001	217,805	0	80:40:20	100			"	Chemical
1998-1999	304,495	0	80:40:20	100			"	Chemical
1996-1997	400,241 (wheat)	0	80:40:20	100			"	Chemical

Table 3. Current and emerging constraints to wheat production

Environmental constraint **Abiotic**	**YES/NO**	**Description of constraint**	**Area affected** *hectares or % of total area*	**Typical yield loss** *range (%)*
Low rainfall	Yes	Rainfall distribution and drought	100	
Declining water resources (for irrigation)	Yes	Excessive pumping	100	
Heat				
Cold				
Salinization				
Soil physical degradation	Yes	Crusting due to heavy tillage	80	
Micro-element deficiency (e.g., Zn, Bo)	No			
Micro-element toxicity (e.g., Al, Bo)				
Lodging	No			
Other				
Biotic				
Diseases		Yellow rust, leaf rust, foliar blights	10	15-25
Pests				
Weeds	Yes	Avena fatua, Eleusine sp, and Poa sp	100, less 50, less 50	Unknown
		Amaranthus sp, Sicyos sp, and Portulaca sp	80, 70, 50	Unknown
Socioeconomic constraint				
Credit				
Seed availability/quality				
Fertilizer availability	No			
Fungicide/pesticides/herbicides availability/cost	Yes	Highly effective herbicides are expensive and/or unavailable	100	
Mechanization/access to suitable machinery	Yes	Machinery represents a high percentage of total production costs	100	
Labor	Yes	Migration to large cities and to USA	Unknown	
Transport				
Grain price/ marketing	Yes	Farmers claim higher grain prices	100	
Conflict with other crop or livestock systems				

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	YES/NO	Description of constraint	Priority (Highest, high, moderate, low, not)	Approx investment required $
Field station operations (budget, land, staff, etc.)	Yes	Reduced budget for field operation	High	NA
Field machinery	Yes	Planting machines	Moderate	
Technical assistance staff	No			
Scientific expertise (genetics, pathology, agronomy, etc.)	No			
Socioeconomic expertise (market & impacts analysis, etc.)	No			
Labs/instruments (e.g., quality LAB, MAS, dryers, etc.)	No			
Computers/software/GIS	No			
Controlled growth environments	Yes	Growth cabinets and greenhouses	Highest	In process
Access to genetic resources/storage	No			
Training resources (classrooms, etc.)	No			
Transport	No			
Resources to support collaboration & information sharing	No			
Other				

Table 5. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance 1-6*	Example of partnership Optional
Farmer groups	1	Juchitepec farmers, with more than 20 years of close cooperation with the rainfed wheat program, have made possible not only the release of new wheat varieties, but also ensured that the released varieties reached farmers' fields.
Local private companies	6	
International centers	2	The close cooperation of CIMMYT with INIFAP in the year 2000 allowed us to release Juchi F2000, Nahuatl F2000, Tlaxcala F2000 and Rebeca F2000 for the rainfed areas, among many others for the irrigated areas of Sonora, Sinaloa and Baja California Norte.
Foreign research institutes	5	
Multinationals	6	
NGOs	6	

*Ranking (1=most important, 6=least important)

Table 6. Most useful /desirable outputs from CGIAR centers

CIMMYT output	Specify	Priority
Germplasm		
Advanced lines with generic traits (yield, disease res., etc.)	Advanced lines with high yield potential and good industrial quality, with durable type of rust resistance and drought tolerance for rainfed areas.	Highest
Segregating bulks (F2 onwards)		
Genetic resources		
Training/knowledge sharing		
Basic training for younger scientists		
Advanced courses for mid-career scientists		
Specialized visits of individual scientists, e.g., to CIMMYT		
Visits of CIMMYT scientists to your program		
Methodologies/Information/Publications on		
Breeding (e.g., international nursery reports; IWIS, etc.)	International nurseries such as the ESWYT and IBWSN	Highest
Pathology and pest control		
Genetics (quantitative and molecular)		
Pre-breeding and genetic resources		
Physiology (crop and/or cellular)		
Statistics and experimental design		
Crop management	Advances in crop management and results of long-term experiments for cropping systems.	High
Participatory methods		
Seed technolgy		
Social science and economic analysis		
Training methods		
Software support for databases, GIS, websites, etc.		

Challenges to Wheat Production in Morocco

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Wheat production is a major farm activity that has an important implication on the national economy of Morocco. On average, about three million hectares of wheat are grown annually in Morocco with nearly equal share between bread wheat and durum. The average wheat area cropped per farm is less than 5 ha, implying that most wheat production is undertaken by resource-poor farmers with small holdings. The total wheat area and production is mainly rainfed (about 94% and 74%, respectively) and takes place in drought-prone environments characterized by relatively low rainfall (between 200 and 450mm), high variable precipitation pattern and high occurence of drought. These translate into large inter-annual fluctuations. Moreover, abiotic stresses, e.g., terminal heat, and cold represent serious production constraints that may severely inhibit crop growth. These abiotic stresses are frequently exacerbated by biotic stresses, e.g., diseases, especially rusts, septoria, and root rots, and insects, especially Hessian fly, that severely inhibit crop growth and cause significant reductions in grain yield.

Wheat improvement program of Morocco has benefited greatly from its close collaboration with CIMMYT and the joint CIMMYT/ICARDA wheat program. As a result, over 40 varieties derived from CIMMYT/ICARDA germplasm were released in Morocco. Despite the large number of varieties released, the total area devoted to modern varieties is planted only with a few ones. The reason is the long time lag between the time of release of a variety and the time of its adoption by farmers. This situation is due to weaknesses in the seed production and delivery system, combined to targeted extension programs which are necessary to enable farmers to fully exploit developed technologies and reap the potential gains embodied in new varieties. With regard to crop management, research in Morocco has developed technologies that can boost wheat yield and production, e.g., integrated crop management, supplemental irrigation, reduced/no-till system, for water and soil productivity. Despite research results on the no-till system, the acreage is still very limited.

Insufficient number of scientists with high level of expertise, allocation of funds to research activities and access to information are among the current and emerging constraints to wheat improvement research activities. The relative importance of research partnerships to achieve the national wheat program goals reside mainly in (i) CG Centers helping in training, germplasm exchange, knowledge and technology sharing, developing joint projects, and capacity building; (ii) farmers groups involved in participatory farmers and community approach and technology transfer based on integrated ecosystem approach; and (iii) foreign research institutes collaboration in developing common projects, and networks.

The most useful and desirable outputs from CGIAR Centres still concern sharing of germplasm, especially advanced lines for northern zones, mountains and irrigated areas with generic traits (high yield potential, combined disease and hessian fly resistance, heat and drought tolerance, and quality); training and knowledge sharing through advanced courses for mid career scientists (on wheat improvement, biotechnology and quality), and mutual scientists' visits; development of mmethodologies, information system and publications flow.

Morocco

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Table 1. Cultivars grown and released in irrigated and rainfed areas, 1955-present

(i) IRRIGATED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	100%	Not used	4.4	Not used	7	Tomouh	Razzak	2.2
1985-1995	100%	Not used	3.8	Not used	14	Sebou	Tensift	3
1975-1985	100%	Not used	3.2	Not used	5	Karim	Marzak	5
1965-1975	100%	Not used	2.5	Not used	2	Kyperounda	Cocorit	10
1955-1965	100%	Not used	2	Not used	3	Oued Zanati	Zeramek	15

(ii) RAINFED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	90%	10%	1.8	0.7	7	Tomouh	Irden	5
1985-1995	70%	30%	1.2	0.5	14	Oum Rabia	Bel Bachir	8
1975-1985	40%	60%	1.5	0.7	5	Karim	Marzak	12
1965-1975	30%	70%	1.6	0.5	2	Kyperounda	Cocorit	16
1955-1965	20%	80%	1.2	0.6	3	Oued Zanati	Zeramek	20

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

(i) IRRIGATED AREAS

2 yr period	Conventional tillage *hectares sown*	Reduced/zero tillage *hectares sown*	Average N:P:K applied *kg/ha*	Fully mechanized *% of area*	Sown on flat *hectares sown*	Sown on raised beds *hectares sown*	Gravity:sprinkler irrigation *ratio*	Irrigation applied *mm or frequency*
2003-2004	430,000	0	180:100:60	80	430,000	0	40/60	150-200mm
2002-2003	395,000	0	180:100:60	75	395,000	0	50/50	120-150mm
2000-2001	335,000	0	240:60:60	70	335,000	0	60/40	100-120mm
1998-1999	300,000	0	280:60:90	65	300,000	0	65/35	100-120mm
1996-1997	280,000	0	300:75:90	60	280,000	0	70/30	100-120mm

(ii) RAINFED AREAS

2 yr period	Conventional tillage *hectares sown*	Reduced/zero tillage *hectares sown*	Average N:P:K applied *kg/ha*	Fully mechanized *% of area*	Annual cropping *hectares sown*	Cereal-fallow *hectares sown*	Weed control (grasses) *methods*	Broadleaf weeds *methods*
2003-2004	1,110,500	Limited	60:45:00	75			Use herbicides	Use herbicides
2002-2003	1,092,900	Limited	60:45:00	70			Use herbicides	Use herbicides
2000-2001	976,700	Limited	40:45:20	60			Use herbicides	Use herbicides
1998-1999	1,079,100	Very limited	40:45:20	50			Use herbicides	Use herbicides
1996-1997			40:45:20	40			Use herbicides	Use herbicides

Table 3. Current and emerging constraints to wheat production

Environmental constraint Abiotic	YES/NO	Description of constraint	Area affected ha or % of tot. area	Typical yield loss range (%)
Low rainfall	Yes	Drought	70% of total area	20% to 50%
Declining water resources (for irrigation)	Yes		50% of total irrigated area	10% to 20%
Heat	Yes	High temperature during grain filling stage	30% of total area	3-5%
Cold	No			
Salinization	No	Problem in arid and semiarid irrigated land	5% of total area	5%
Soil physical degradation	Yes	Tillage implements and mismanagement	50% of total area	5-15%
Micro-element deficiency (e.g., Zn, Bo)	No			
Micro-element toxicity (e.g., Al, Bo)	No			
Lodging	Yes	In some areas, but not at large scale		
Other	No			
Biotic				
Diseases	Yes	Leaf rust, Septoria, Root rot	70%, 30-40%, 20-30%	30%, 15%, 15%
Pests	Yes	Hessian fly	60%	30%
Weeds	Yes	Avena sterilis, Bromus rigidus, Phalaris spp. Emex, Astragalus, Calendula, Sinapsis,	Most cereal areas	15-20%
Socioeconomic constraint				
Credit	No			
Seed availability/quality	Yes	High demand and unavailability of some varieties, low rate of use of certified seed		
Fertilizer availability	No			
Fungicide/pesticides/herbicides availability/cost	Yes	Cost		
Mechanization/ access to suitable machinery	Yes	Not available in some areas		
Labor	No			
Transport	No			
Grain price/ marketing	No			
Conflict with other crop or livestock systems	No			

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	YES/NO	Description of constraint	Priority (Highest, high, moderate, low, not)	Approx investment required $
Field station operations (budget, land, staff, etc.)	Yes	Availability of funds on time	High	
Field machinery	Yes	Need for new equipment, machinery old	Highest	300,000
Technical assistance staff	Yes	Retirement, need to recruit	High	Government policy
Scientific expertise (genetics, pathology, agronomics, etc.)	Yes	Insufficient # of plant breeders, pathologists, chemists,…	Highest	Government policy
Socioeconomics expertise (market & impacts analysis, etc.)	Yes	Impact assessment	High	
Labs/instruments (e.g., quality LAB, MAS, driers, etc.)	Yes	Need for NIRS, dryers	High	150,000
Computers/software/GIS	No			
Controlled growth environments	Yes	Greenhouse facility and management	Moderate	
Access to genetic resources/storage	No			
Training resources (classrooms, etc.)	No			
Transport	Yes	Insufficient # of vehicles	Moderate	100,000
Resources to support collaboration & information sharing	Yes	Insufficient funds to support such activities	High	
Other	Yes	International collaboration	Moderate	

Table 5. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance 1-6*	Example of partnership Optional
Farmer groups	1	Participatory farmers and community approach and technology transfer based on integrated ecosystem approach
Local private companies	3	Agreement for seed production and marketing new adapted varieties and other inputs to promote uses
International centers	1	CG Centers for training, germplasm exchange, knowledge and technology sharing, developing joint projects, and capacity building
Foreign research institutions	2	Developing collaborative projects and networks among UE and regional research institutes
Multinationals	4	Collaboration, information sharing, and networks
NGOs	3	Collaboration in rural development projects and expertise, and capacity building

*Ranking (1=most important, 6=least important)

Table 6. Most useful /desirable outputs from CGIAR centers

CIMMYT output	Specify	Priority
Germplasm		
Advanced lines with generic traits (yield, disease res., etc.)	Yield potential, combined leaf rust and Hessian fly resistance and quality	Highest
Segregating bulks (F2 onwards)	Irrigated areas	High
Genetic resources	For germplasm exchange, breeding and special study	High
Training/knowledge sharing		
Basic training for younger scientists	In areas of wheat improvement, screening for diseases and pests, biotechnology, quality & statistics	High
Advanced courses for mid-career scientists	Wheat improvement, biotechnology, and quality	Highest
Specialized visits of individual scientists, e.g., to CIMMYT	Use of biotechnology tools in drought resistance, Hessian fly resistance, leaf rust	High
Visits of CIMMYT scientists to your program	Expertise in wheat improvement, assistance in strategy development, Workshops	Highest
Methodologies/Information/Publications on		
Breeding (e.g., international nursery reports, IWIS, etc.)	Annual reports, IWIS, publications	High
Pathology and pest control	Reports, pamphlets, manuals	Highest
Genetics (quantitative and molecular)	Reports, publications, manuals	High
Pre-breeding and genetic resources	Catalog, manuals, reports; plant genetic res. information system (data management & documentation)	High
Physiology (crop and/or cellular)	Scientific publications, reviews, approaches, screening	High
Statistics and experimental design	Experimental design and data analysis	Highest
Crop management	Integrated crop management, improvement in WUE & NUE, no-till and residue management, bed planting	Highest
Participatory methods	Methodological approaches, technology transfer, publications, manuals	High
Seed technolgy	Seed production and technology manuals	Low
Social science and economic analysis	World wheat facts and trends/overview and outlook, policy and institutional analysis	High
Training methods	Manuals	Moderate
Software support for databases, GIS, websites, etc.	Softwares, networks, websites	High

Challenges to Wheat Production in Nepal

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Millions of resource poor farmers in Nepal derive their livelihood from wheat (*Triticum aestivum* L.) cultivation. In 2005, Nepal produced 1.440 million ton wheat from an area of 0.765 million hectares at 2.134 t/ha yield. The average national wheat productivity has increased at the rate of about 3.88% over the last 11 years. However, there are many abiotic, biotic, and socio-economic constraints to successful wheat cultivation in Nepal. The major abiotic stresses are terminal heat, declining soil fertility, wheat sterility, and drought. The important biotic stresses include diseases (yellow rust, foliar blight and leaf rust), insect-pest (aphid and weevil), and weeds (*Phalaris minor, Polypogon fugax* and *Chenopodium spp*.). The socio-economic constraints include lack of credit, unavailability of quality seed, high price and unavailability of fertilizers and farm machineries on time, shortage of labor during harvest, and low benefit-cost ratio from wheat cultivation. In the background of the above constraints, the wheat research activities in Nepal aim at increasing productivity, profitability and sustainability of wheat based farming systems. Options in terms of improved cultivars and technology are continuously being made available to the wheat growers and industries. Several improved wheat cultivars with high grain yield, bold kernels, resistance to prevalent diseases and pests, and tolerance to abiotic stresses that fit in the farmers' cropping systems have been developed. Resource conservation technologies such as surface seeding, zero and minimum tillage, using zero till seed drill and power tiller seed drill respectively, are being promoted through a pluralistic approach. Participatory varietal selection is being expanded for identifying cultivars suitable to specific agro-climatic and management conditions. Community based and farmers' collaborated seed production activities are being promoted to make improved seed available to the wheat growers. However, there are still several daunting challenges to improving productivity and profitability of wheat-based farming system in Nepal. While yield potential is continuously being improved, a great deal of efforts is needed towards efficiently managing wheat and improving socio-economic constraints. This is especially true for the hilly areas of the country where the poorest of the poor live. Wheat must be produced at a lower cost under increasing threats from abiotic and biotic stresses. The present 1.3% of the total wheat area under conservation tillage needs to be expanded. Participatory varietal selection and community based seed production must be accelerated to deliver cultivars as per need of the farmers and make seeds available to rural wheat growers. Additional sources of resistance to yellow rust and foliar blight are needed to improve the level of resistance in the commercial cultivars. New germplasm and technology are needed to breed wheat with heat tolerance. Early maturing rice cultivars that could allow for timely wheat seeding in the rice-wheat cropping system are also needed. Investment in wheat research must be increased in terms of infrastructures and manpower. Government policies in terms of credit and input availability, marketing, and support price need to be improved in order to alleviate poverty and to improve the livelihoods of the resource constrained wheat farmers in Nepal.

Nepal

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Table 1. Cultivars grown and released in irrigated and rainfed areas, 1955-present

(i) IRRIGATED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	370,946	1,063	2.4	1	3	Bhrikuti (150,000 ha)	Nepal 297 (100,000 ha)	0.8 ha
1985-1995	327,915	1,960	2.1	1	4	Nepal 297 (140,000 ha)	UP 262 (30,000 ha)	1.1 ha
1975-1985	197,434	2,983	1.55	1	7	UP 262 (70,000 ha)	Vinayak (50,000 ha)	1.13 ha
1965-1975	106,925	3,454	1.4	1.1	4	RR-21 (= Sonalika) (80000 ha)	Lerma-52 (15,000 ha)	1.21 ha
1955-1965	990	2,651	1.23	1.1	4	Lerma-52 (990 ha.)	Dabdi Local (2,000 ha)	1.23 ha

(ii) RAINFED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	268,616	34,374	2	0.9	3	Anapurna-4 (60,000 ha)	Annapurna-1 (40,000 ha)	0.8 ha
1985-1995	247,095	76,401	1.6	0.9	4	Annapurna-1 (30,000 ha)	Annapurna-3 (30,000 ha)	1.1 ha
1975-1985	155,126	96,457	1.24	0.9	2	RR 21 (=Sonalika) (50,000 ha)	Triveni (30,000 ha)	1.13 ha
1965-1975	106,125	111,696	1.23	0.9	3	RR 21 (= Sonalika) (40,000 ha)	Lerma-52 (30,000 ha)	1.21 ha
1955-1965	2,970	103,389	1.2	1	2	Dabdi Local (50,000 ha)	NP series (30,000 ha)	1.23 ha

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

(i) IRRIGATED AREAS

2 yr period	Conventional tillage *hectares sown*	Reduced/zero tillage *hectares sown*	Average N:P:K applied *kg/ha*	Fully mechanized *% of area*	Sown on flat *hectares sown*	Sown on raised beds *hectares sown*	Gravity: sprinkler irrigation *ratio*	Irrigation applied *mm or frequency*
2004-2005	381,500	10,000	70:40:20	0	391,500	0	1:00	1 to 3
2002-2003	376,387	5,000	60:40:10	0	381,387	0	1:00	1 to 3
2000-2001	355,977	3,000	50:30:05	0	358,977	0	1:00	1 to 3
1998-1999	357,849	1,000	50:30:00	0	358,849	0	1:00	1 to 3
1996-1997	372,378	0	40:25:00	0	372,378	0	1:00	1 to 3

(ii) RAINFED AREAS

2 yr period	Conventional tillage *hectares sown*	Reduced/zero tillage *hectares sown*	Average N:P:K applied *kg/ha*	Fully mechanized *% of area*	Annual cropping *hectares sown rainfed area sown only)*	Cereal-fallow *hectares sown*		Weed control (grasses) *methods*	Broadleaf weeds *methods*
2004-2005	383,500	0	50:30:05	0	383,500	325,975	(rice-wheat & maize-wheat)	Approximately 5% farmers use herbicides, rest do hand weeding	Approx. 10% farmers use herbicides, rest do hand weeding
2002-2003	381,022	0	50:30:00	0	381,022	323,869	″ ″		
2000-2001	282,053	0	50:30:00	0	282,053	236,925	″ ″		
1998-1999	281,953	0	40:25:00	0	281,953	236,841	″ ″		
1996-1997	292,582	0	30:25:00	0	292,582	245,769	″ ″		

Table 3. Current and emerging constraints to wheat production

Environmental Constraint	**YES/NO**	**Description of constraint**	**Area affected**	**Typical yield loss**
Abiotic			***hectares or % of total area***	***range (%)***
Low rainfall	Yes	Monsoon climate, almost 44% wheat area is under rainfed condition, winter rains are uncertain and not adequate	44% of total wheat area	15 to 20%
Declining water resources (for irrigation)	No	Available water resources are under utilized/not exploited in full scale		
Heat	Yes	Post-anthesis exposure to high temperature and westerly hot winds during postanthesis	About 125,000 hectares of late planted wheat area	25 to 35%
Cold	No	Some cold injury occurred in high mountain areas, but not a serious problem		
Salinization	No			
Soil physical degradation	Yes	Hard plow pan due to rice transplanting; organic matter depletion due to removal of crop residues	85% of total wheat sown followed by rice	Not known
Micro-element deficiency (e.g., Zn, Bo)	Yes	Bo deficiency induced wheat sterility is common, Zn & other micro-element deficiencies exist	About 60% of wheat area might be affected	Not known
Micro-element toxicity (e.g., Al, Bo)	Yes	Al toxicity in acid soils of hilly areas might exist		
Lodging	No			
Other (Major nutrients (NPK) deficiencies & poor irrigation management)	Yes	Low native NPK as well applied NPK are much lower than required, poor quality fertilizers, lack of irrigation infrastructure	Deficiencies are common to most of the wheat area	About 1 t/ha.
Biotic				
Diseases	Yes	Yellow rust is big problem in the hills and varieties lack genes for durable resistance. Leaf rust is under control	About 20 to 30% of total wheat area affected annually by yellow rust, and about 40% of area is affected by HLB in varying degrees	10 to 15% by yellow rust
Yellow rust, HLB complex and Leaf rust		HLB complex is common in the Terai and adequate genetic resistance is available in the germplasm		About 10% by HLB
Pests	No	Aphid infestation is an increasing trend with no significant yield loss	Not yet assessed	Not attempted
Aphid and weevil				
Weeds: Phalaris minor, Polypogon fugax and Chenopodium spp.)	Yes	Phalaris minor is common, Polypogon fugax is becoming a problem in depressional rice-wheat land		5 to 10%
Socioeconomic constraints				
Credit	Yes	Not easily accessed in rural areas and a complicated process	About 50% wheat area	Not known
Seed availability/quality	Yes	Seed replacement rate is low (6% only), quality of farmers' seed is very poor	About 600,000 hectares affected	10 to 15%
Fertilizer availability	Yes	Fertilizers are not available on time	About 600,000 hectares affected	About 15 to 20%
Fungicide/pesticides/herbicides availability/cost	No			
Mechanization/ access to suitable machinery	Yes	Suitable machinery is not easily accessed by farmers, also expensive	About 50% wheat area affected	Not known
Labor	Yes	Acute shortage of agricultural labor, late harvesting - shattering losses	10% area affected	5% loss
Transport	No			
Grain price/ marketing	Yes	Farm gate prices are lower, not matched with production cost	Applied to all farmers	
Conflict with other crop or livestock systems	No	Not much, some competition with winter legumes		

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	YES/NO	Description of constraint	Priority *(Highest, high, moderate, low, not)*	Approx investment required $
Field station operations (budget, land, staff etc.)	Yes	Heavy cut in operational budget, difficult to operate off-season site, downsized the breeding program, cut down testing sites, etc.	Highest	$50,000 annually
Field machinery	Yes	Managing the research fields with 20-year old machinery, need modern planting equipment	High	100,000
Technical assistance staff	No			
Scientific expertise (genetics, pathology, agronomy , etc.)	Yes	Present scientific staff are near retiring age, there is no lateral entry in wheat breeding	High	
Socioeconomic expertise (market & impacts analysis, etc.)	Yes	At present there is no socioeconomic expertise appointed directly to wheat improvement program	High	
Labs/instruments (e.g., quality LAB, MAS, dryers, etc.)	Yes	Need quality lab, germplasm storage facilities, dehumidifiers, dryers, greenhouse, automated weather station, etc.	High	100,000
Computers/software/GIS	Yes	GIS facility does not exist in the program but needed at least GPS machines are required	High	50,000
Controlled growth environments	yes	Such facility needed specially for wheat physiological studies	Moderate	20,000
Access to genetic resources/storage	Yes	No gene bank facility in Nepal to store valuable genetic resources	Highest	15,000
Training resources (classrooms, etc.)	Yes	Publications, handouts, kits, models, supplies	Moderate	20,000
Transport	Yes	20 years old vehicles and few in numbers to visit research stations, outreach sites and farmers fields	Moderate	50,000
Resources to support collaboration & information sharing	Yes	Lack of budget for information exchange, internet connections, database creation and use	High	30,000
Other	Yes	Lack of visits and interactions with regional and interactions programs/centers, workshops, conferences	High	25,000

Table 5. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance 1-6*	Example of partnership Optional
Farmer groups	1	Participatory research and development
Local private companies	2	Seed production and dissemination, marketing, industrial quality information
International centers	1	Germplasm exchange, training and visits, information sharing, etc.
Foreign research institutions	2	Germplasm exchange, training and visits, information sharing, etc.
Multinationals	3	Imports potential and product information sharing
NGOs	2	Collaborative research and development

* Ranking (1=most important, 6=least important)

Table 6. Most useful /desirable outputs from CGIAR centers

CIMMYT output	Specify	Priority
Germplasm		
Advanced lines with generic traits (yield, disease res., etc,)	Yield, resistant to rusts, HLB, IQ, heat & drought. (Preferably white grain types), bold grains, early to medium maturity	High
Segregating bulks (F2 onwards)	Semi-finished bulks (F4 or F5), preferably white grain types	Moderate
Genetic resources	Yield components, doubled haploids, IQ, information on germplasm and cultivars	Moderate
Training/knowledge sharing		
Basic training for younger scientists	Short-term training on efficient breeding techniques, disease evaluation and management (lab + field), biometrics, resource management	High
Advanced courses for mid-career scientists	In the forms of training in specialized field/techniques, and MS and PhD research	High
Specialized visits of individual scientists, e.g., to CIMMYT	As visiting scientist, updating CIMMYT's latest advancements	High
Visits of CIMMYT scientists to your program	Often needed to see progress made by the Natl' Programs, interactions on scientific developments	Moderate
Methodologies/Information/Publications on		
Breeding (e.g., international nursery reports; IWIS, etc.)	Information on latest breeding methods, intl' nursery reports in timely fashion, updated ÍWIS, online access to CRIL	High
Pathology and pest control	Updated gene postulation reports of CIMMYT's bread wheat advanced lines and parents	High
Genetics (quantitative and molecular)	Inheritance information of traits, information on markers linked to traits	High
Pre-breeding and genetic resources	Germplasm with genes from wild species for abiotic stress tolerance and resistance to yellow and leaf rusts and foliar blight	
Physiology (crop and/or cellular)	Heat stress, water logging, drought stress related information and germplasm	Moderate
Statistics and experimental design	Training and softwares for alpha design generation and analysis, stability analysis, biplots	High
Crop management	Latest advances in crop management	Moderate
Participatory methods	Effective and proven participatory methodologies to deliver technologies	Moderate
Seed technology	Information on recent advances on seed production technology specially on variety maintenance	Moderate
Social science and economic analysis	Information of diagnostic, base line survey, impact assessment packages	Moderate
Training methods	Training manual in different aspects of wheat crop, biometrics, disease identification and scoring, bioinformatics	Moderate
Software support for databases, GIS, websites, etc	Necessary software support are required for GIS, GPS, internet, decision support	High

Increasing Wheat Productivity in Pakistan

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In Pakistan, introduction of modern varieties and use of chemical fertilizers helped greatly to improve national average wheat yield from 0.75 tonnes to 2.6 tonnes during 1955-2005. The development and release of about 68 irrigated and 19 rainfed improved wheat cultivars in the country contributed toward the adoption of modern varieties on 7.83 million hectares which is around 95% of total wheat area. Presently, average wheat yield of modern varieties is around 2.6 and 1.2 t / ha in irrigated and rainfed area, respectively. Farmers are not able to achieve the potential of wheat cultivars because of poor crop management and costly inputs. During 1995-2005, wheat farmers of rice-wheat area of Punjab are experiencing the reduced tillage / zero tillage nearly on 1.0 million hectares, however, it could not make inroads other cropping system like cotton-wheat and rain fed area. In irrigated area, the farmers are applying 208 Kg of NPK per hectare. On the other hand, rainfed farmers are applying 42 Kg of N P / hectare. The NP ratio is around 3:1 and use of potash is minimal. With the introduction of wheat threshers and combine harvester the fully mechanized area stand at 10% of the total area. In the country, most of the operation like land preparation, and threshing are fully mechanized; however, most of the harvesting is still done by hand. Wheat production is facing challenges like drought in rain fed area, declining water availability, terminal heat, yellow rust , leaf rust, aphids and weeds infestation. Wheat productivity is also affected by late planting, lower certified seed availability and costly input, like fertilizers and herbicides. The research centers working for the wheat improvement in the country needs the training for their scientists and required resources to carry out research work to meet the further challenges.

Pakistan

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Table 1. Cultivars grown and released in irrigated and rainfed areas, 1955-Present

	Irrigated area				
Period	Modern Varieties hectares sown	Landraces hectares sown	Avg MV yield t/ha	Avg landraces yield t/ha	Cultivar released numbers
1995-05	6,650,000	350,000	2.6	0.6	13
1985-95	5,920,000	510,000	2.12	0.65	15
1975-85	4,480,000	980,000	1.98	0.76	26
1965-75	2,360,000	2,270,000	1.66	0.75	13
1955-65	-	3,870,000	-	0.89	1
	Rainfed area				
Period	Modern Varieties hectares sown	Landraces hectares sown	Avg MV yield t/ha	Avg landraces yield t/ha	Cultivar released numbers
1995-05	1,180,000	70,000	1.12	0.4	7
1985-95	1,260,000	120,000	1.03	0.42	8
1975-85	1,230,000	280,000	0.89	0..45	1
1965-75	610,000	590,000	0.81	0.44	3
1955-65	-	968,000	-	0.48	-

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

	Irrigated area					
2 yr period	**Conventional tillage hectares**	**R T / zero tillage hectares**	**Average N: P: K kg/ha**	**Fully mechanized % area**	**Sown on flat hectares**	**Sown on raised beds hectares**
2004-2005	6,095,400	1,001,000	150:50:01	10	7,096,400	-
2002-2003	6,335,400	728,600	155:52:01	8	7,064,000	-
2000-2001	6,889,200	146,800	143:39:01	7	7,036,000	-
1998-1999	7,046,200	6,800	131:37:01	5	7,053,000	-
1996-1997	6,832,600	400	122:36:03	5	6,833,000	-

	Rainfed area					
2 yr period	**Conventional tillage hectares**	**R T / zero tillage hectares**	**Average N: P: K kg/ha**	**Fully mechanized % area**	**Annual cropping hectares**	**Cereal fallow hectares**
2004-2005	1,194,000	-	60:23:00	1	477,000	716,400
2002-2003	1,060,000	-	60:23:00	1	424,000	636,000
2000-2001	1,082,000	-	55:22:00	<1	432,000	649,200
1998-1999	1,293,000	-	54:20:00	<1	517,000	775,800
1996-1997	1,398,000	-	50:18:00	<1	559,000	838,800

Table 3. Current and emerging constraints to wheat production.

Environmental constraints	YES/NO	Description of constraint	Area affected (hectares / % of area)	Typical yield losses range (%)
Low rainfall	Yes	Low moisture at planting and during season	1,000,000	30 - 50 %
Declining water resources (for irrigation)	Yes	Low rainfall in plains and snow at hills	5,000,000	10-15 %
Heat	Yes	Terminal heat during grain filling period	4,000,000	5-10%
Cold	No	-		
Salinization	Yes	Salinity in the Punjab and Sind area	1,000,000	7-12%
Soil physical degradation	Yes	Poor soil tilth, soil compaction	20% of total area	10-15%
Micro-element deficiency (e.g., Zn,Bo)	Yes	Micronutrient deficiency because of alkaline pH	50% of total area	15-25%
Micro-element toxicity (e.g., Al,Bo)	No	-	-	-
Lodging	Yes	Occasionally forced lodging at maturity	-	1-10%
Other	-	-	-	-
Pests				
Diseases	Yes	Yellow rust, leaf rust, powdery mildew	1,250,000	5-30%
Pests	Yes	Aphids	2,000,000	Negligible
Weeds (grass and broadleaf)	Yes	Phlaris minor, Avena sativa, Chenopodium album, Convolvulus arvensis, Carthemis oxicanthus	80-90% of total area	Up to 35%
Socio economic constraints				
Credit	Yes	Availability to small farmers is unsatisfactory	Up to 50% of area	Up to 35%
Seed availablity / quality	Yes	Only 20% certified seed is available	Up to 50% of area	5%
Fertilizer availability	Yes	High cost of phosphatic fertilizers	3,500,000	10-30%
Fungicide/pesticides/herbicides availability/cost	Yes	Availability and quality	-	-
Mechanization/access to suitable machinery	Yes	Lack of machinery (drills and combine harvester)	-	-
Labor	Yes	Availability at harvesting is a problem	-	-
Transport	No	-	-	-
Grain price/marketing	No	-	-	-
Conflict with crop or livestock systems	Yes	Late planting is an issue in cotton, rice and sugarcane area	-	-

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	YES/NO	Description of constraint	Priority (Highest, high, moderate, low, not)	Approx investment $
Field station operations (budget, land, staff, etc.)	Yes	Operational	Highest	-
Field machinery	Yes	Old machinery	Highest	-
Technical assistance staff	No	-	-	-
Scientific expertise (genetics, patholology, agronomy)	No	-	-	-
Socioeconomic expertise (market & impacts analysis)	No	-	-	-
Labs/instruments (e.g., quality labs, dryers, etc.)	Yes	-	High	-
Computers/software/G/S	Yes	GIS	High	-
Controlled growth environments	Yes	-	High	-
Access to genetic resources/ storage	No	-	Low	-
Training resources (classrooms, etc.)	No	-	Low	-
Transport	Yes	-	Moderate	-
Resources to support collaboration & information sharing	Yes	-	Moderate	-
Other	-	-	High	-

Table 5. Releative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance 1-6*	Example of partnership optional
Farmer groups	2	-
Local private companies	3	-
International centers	1	-
Foreign research institutes	2	-
Multinationals	4	-
NGOs	2	-

Table 6. Most useful/desirable outputs from CGIAR centers

CIMMYT output	Yes / No
Germplasm	
Advanced lines with generic traits(yield, disease res., etc.)	Yes
Segregating bulks(F2 onwards)	Yes
Genetic resources	Yes
Training/knowledge sharing	**Yes**
Basic training for younger scientists	Yes
Advanced courses for mid-career scientists	Yes
Specialized visits of individual scientists, e.g., to CIMMYT	Yes
Visit of CIMMYT scientists to your program	Yes
Methodologies/Information/Publication on	**Yes**
Breeding (e.g., international nursery reports, IWIS, etc.)	Yes
Pathology and pest control	Yes
Genetics (quantitative and/or cellular)	Yes
Statistics and experimental design	Yes
Crop management	Yes
Participatory methods	Yes
Seed technolgy	Yes
Social science and economic analysis	Yes
Training methods	Yes
Software support for data bases, GIS, websites, etc.	Yes

Wheat Yield Potential in Sudan

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Although wheat (*Triticum aestivum* L.) is an old crop in Sudan, but until the 1960s its production was restricted to the relatively favorable environment of the northern Sudan. Increased consumption, resulted from growing population, urbanization and changing food habits led to the expansion of the crop production southwards in the heat-stressed environments of the central clay plains. A number of high yielding and heat tolerant cultivars were released for cultivation in the new less favorable areas. Close collaboration with international and regional research institutes enhanced the development of elite production technologies. Consequently, annual areas under wheat increased from 21,000 ha during the period 1955-65 with an average yield of 1.5 ton/ha to 143000 ha during 1965-1975 with an average yield of 1.2 ton/ha and then to 263,000 ha during the period 1985-95 with an average yield of 1.5 ton/ha. During the period 1995-2005, areas under wheat decreased to 175000 ha annually with an average yield of 2.0 ton/ha due to many factors including the unavailability of credit and inputs at the right time in addition to the high competition from the low-priced imported wheat. Fluctuation in yield /ha was mainly due to variation in areas of wheat in the less favorable environment of central Sudan. In fact, most of the areas under wheat during the period 1955-1972 and 1995-2005 were in the northern Sudan. Almost all areas under wheat production are fully irrigated by gravity with an equivalent of about 100 mm of water applied every two weeks. Land preparation throughout the production areas is conventional. Similarly, sowing is on flat. Wheat in central Sudan is fully mechanized while it is partially mechanized in the northern Sudan. Wheat productivity is affected by a number of environmental constraints including heat and moisture stresses, low soil fertility, water logging, weed and aphid infestations. Unavailability of credit and production inputs at the right time in addition to lack of clear policies are serious socio-economic constraints. It is expected that the recent achievements as well as the anticipated technologies in wheat research regarding improved cultivars, crop management etc if transferred to farmers would greatly enhance productivity. It is realized that quality characteristics regarding nutritional and technological values are major considerations for successful competitive and sustainable production.

Sudan

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Table 1. Cultivars grown and released in irrigated and rainfed areas, 1955-present

	(i) IRRIGATED AREAS							
Period	Modern varieties (MV) hectares sown*	Landraces hectares sown	Avg MV yield t/ha**	Avg landrace yield t/ha	Cultivars released number	Dominant variety 1 hectares sown	Dominant variety 2 hectartes sown	Avg farm size ha
1995-2005	175,000	0	2.0	0	5	90,000	50,000	1.5
1985-1995	263,000	0	1.5	0	3	120,000	80,000	1.5
1975-1985	167,000	0	1.2	0	3	90,000	40,000	1.5
1965-1975	143,000	0	1.2	0	3	90,000	30,000	1.5
1955-1965	21,000	0	1.5	0	3	15,000	5,000	0.5

* hectares sown annually, i.e., average of the period

** Fluctuation in yield per hectare is due to the fact that most of the areas under wheat during 1955-1972 were in the relatively favorable environment of northern Sudan. Then wheat production expanded to the warmer areas of central Sudan before the areas planted with wheat sharply reduced there from 1999 onward.

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

	(i) IRRIGATED AREAS							
2 yr period	Conventional tillage hectares sown*	Reduced/zero tillage hectares sown	Average N:P:K applied kg/ha	Fully mechanized % of area	Sown on flat hectares sown	Sown on raised beds hectares sown	Gravity:sprinkler irrigation ratio	Irrigation applied mm or frequency
2004-2005	340,000	0	86:43:00	40	340,000	0	1:0	100 mm every two weeks
2002-2003	265,000	0	86:43:00	25	265,000	0	1:0	100 mm every two weeks
2000-2001	211,000	0	86:43:00	10**	211,000	0	1:0	100 mm every two weeks
1998-1999	397,000	0	86:43:00	50	397,000	0	1:0	100 mm every two weeks
1996-1997	627,000	0	86:43:00	70	627,000	0	1:0	100 mm every two weeks

* Total of the 2 yr period ** The sharp reduction of wheat area in central Sudan in 2000-01 resulted in the reduction of the percent of fully mechanized areas

Table 3. Current and emerging constraints to wheat production

Environmental constraint	YES/NO	Description of constraint	Area affected	Typical yield loss
Abiotic			hectares or % of total area	range (%)
Low rainfall	No			
Declining water resources (for irrigation)	No			
Heat	Yes	Early and late heat stresses are very common. Sporadic heat stress throughout the season also occurs.	75-100%	30-40% of the affected areas
Cold	No			
Salinization	Yes	Saline and sodic soils in the high terrace soils of northern Sudan (new expansions)	5-10%	50-70% of the affected areas
Soil physical degradation	Yes	Waterlogging, sand movements, etc.	50-60%	10-20% of the affected areas
Micro-element deficiency (e.g., Zn, Bo)	No			
Micro-element toxicity (e.g., Al, Bo)	No			
Lodging	Yes	When old and tall varieties are grown, e.g., Beladi and Giza 155	5-10%	10-15% of the affected areas
Other	Yes	Water pumping and conveying systems (water stress due to poor conditions of the conveying systems)	50-70%	20-30% of the affected areas
Biotic				
Diseases	Yes	Stem and leaf rusts. Localized in the eastern parts of the country	0.20%	20-30% of the affected areas
Pests	Yes	Aphids are the most harmful pest, but termites are localized in certain areas	50%	25-30% of the affected areas
Weeds	Yes	Wild sorghum. Weed flora vary from region to another but some are common Grasses: Sorghum sudanensis, Brachiaria eruciformis, Cynodon dactylon, Broadleaf weeds:, Malpha sp., Sinapis arvensis, Rhyncosia memnonia	70-90%	20-25% of the affected areas
Socioeconomic constraint				
Credit	Yes	Not enough, and even the limited amount is provided to farmers very late		
Seed availability/quality	Yes	No quality seeds are available in some parts		
Fertilizer availability	Yes	Not available at the right time		
Fungicide/pesticides/herbicides availability/cost	No			
Mechanization/access to suitable machinery	Yes	Operation costs and the availability of the suitable machine at the right time		
Labor	No			
Transport	No			
Grain price/ marketing	Yes	Low prices at the time of harvest and the high competition from imported low-cost wheats		
Conflict with other crop or livestock systems	Yes	Winter legumes compete with wheat for land and water in northern Sudan and cause delaying of wheat sowing		

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	YES/NO	Description of constraint	Priority (Highest, high, moderate, low, not)	Approx investment required $
Field station operations (budget, land, staff, etc.)	Yes	Limited budgets for research	Highest	500,000
Field machinery	Yes	Field machinery (small plot seed drills, threshers, etc.) are very old	Moderate	50,000
Technical assistance staff	No			
Scientific expertise (genetics, pathology, agronomy, etc.)	Yes	More capacity building is needed	Moderate	50,000
Socioeconomic expertise (market & impacts analysis, etc.)	Yes	More capacity building is needed	Moderate	50,000
Labs/instruments (e.g., quality LAB, MAS, driyers, etc.)	Yes	Well-equipped laboratory for development of quality wheats is urgently needed	Highest	250,000
Computers/software/GIS	Yes	Computers are available but software/GIS is required	Moderate	20,000
Controlled growth environments	Yes	No controlled growth environments are available	Moderate	100,000
Access to genetic resources/storage	Yes	Very limited storage facility and poor accessibility	High	25,000
Training resources (classrooms, etc.)	Yes	Limited resources for training are available	Moderate	100,000
Transport	Yes	Transportation tools are old and urgently need to be replaced	Highest	100,000
Resources to support collaboration & information sharing Other	Yes	Need to be updated	Moderate	20,000

Table 5. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance 1-6*	Example of partnership Optional
Farmer groups	2	On-farm research, demonstration plots and participation in selection processes
Local private companies	6	Testing newly developed technologies
International centers	1	Collaborative research and assisting in germplasm development
Foreign research institution	4	Collaborative research
Multinationals	3	Net working
NGOs	5	Collaborative research

* Ranking (1=most important, 6=least important)

Table 6. Most useful /desirable outputs from CGIAR centers

CIMMYT output	Specify	Priority
Germplasm		
Advanced lines with generic traits (yield, disease res., etc.)	Advanced lines for yield, diseases and quality	High
Segregating bulks (F2 onwards)	Segregating pops from targeted crosses, e.g., heat	Highest
Genetic resources	Access to genetic resources in areas like heat stress and quality	Moderate
Training/knowledge sharing		
Basic training for younger scientists	Short, medium, and degree training	Highest
Advanced courses for mid-career scientists	Acquiring the latest technologies	High
Specialized visits of individual scientists, e.g., to CIMMYT	Interaction with scientists in different areas	High
Visits of CIMMYT scientists to your program	Knowledge sharing and getting familiar with the exact problems of the program	High
Methodologies/Information/Publications on		
Breeding (e.g., international nursery reports; IWIS, etc.)	Breeding methods, reports, IWIS	Highest
Pathology and pest control	Latest developments, e.g., in new rusts race development etc.	Moderate
Genetics (quantitative and molecular)	MAS, heritability of traits of interest, etc.	Highest
Pre-breeding and genetic resources	e.g., genetic resources for heat tolerance and quality	High
Physiology (crop and/or cellular)	Latest development in stress physiology at all levels	High
Statistics and experimental design	Suitable experimental designs, data collection, analysis and interpretations, and modeling	Highest
Crop management	e.g., bed planting, minimum tillage, etc.	Moderate
Participatory methods	Sharing experiences and methodologies	High
Seed technolgy	Quality seed production and maintenance	Moderate
Social science and economic analysis	Economic analysis of wheat production in stress environments	High
Training methods	Latest training methods and facilities	High
Software support for databases, GIS, websites, etc.	Software for databases GIS, websites, etc.	High

Wheat Yield Potential Improvement in Tajikistan

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Bread in Tajikistan is a staple food product and wheat growing is one of the most important agricultural activities. The total demand of Tajikistan makes about 1,5-2 mln tons of grain. However there is still a deficit of grain, despite the recent production growth. Over the last 10 years wheat areas all over the country increased up to almost 2,5 times. In 2005 about 890,000 tons of grain was produced, and though the demand was not fulfilled. Recent years wheat occupies about 360,000 ha, approximately 60% of which is under irrigation. Expansion of wheat areas led to epiphytotic changes and fungal diseases dissemination. In comparatively humid years with higher amount of precipitation outbreak of yellow rust is observed. Annual production of wheat makes 390–400 thousand tons, from which 65-70% is produced by private sector. However, in spite of production growth, there are scarce changes in wheat yield that in average makes 1,8-1,9 t/ha. The yield in the rainfed area is very low and depends on the amount of precipitation. Quality of the locally produced grain is low. Due to a delay with planting and harvesting of wheat as well as lack of inputs and machinery, the grain is damaged by heat stress, which makes it shriveled. Hence in Tajikistan, known as one of the center of origin of cereals, especially wheat, there is a diversity of wild relatives and landraces. Farmers still grow wheat landraces Surkhak and Safedak in the remote mountainous villages. In the valleys the farmers have more access to the improved varieties. Since 1970-s Tajik farmers used to grow a wheat variety named Siete Cerros 66, which was introduced in Tajikistan through Mexican breeding programs. During recent years a number of wheat varieties and advanced lines were tested in the different agro-ecological zones within the framework of GTZ-CIMMYT Project. Among primary selected genotypes such varieties as Steklovidnaya-24, Jagger-9, Atoi, Sulton 95 and Kenacil became very popular in many zones due to high yield and yellow rust tolerance. Now Jagger-9 dominates under irrigation and Steklovidnaya-24 in the rainfed zone. On the basis of the conducted uniform trials several new varieties were identified as rust resistant and high yielding. Among selected genotypes 6 were submitted to official trials as new varieties - Norman, Tasicar, Armon, Somoni, Ziroat-70 and Alex. As a further expansion of wheat area is not possible, the increase of grain production requires the increase of crop yield at the expense of crop management improvement and introduction of new varieties resistant to diseases, pests, tolerant to abiotic stresses and with good bread making quality.

Tajikistan

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Table 1. Cultivars grown and released in irrigated and rainfed areas, 1955-present

(i) IRRIGATED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	130,000	2,000	3.0	1.5	2	80,000	40,000	50
1985-1995	40,000	3,000	2.5	1.5	4	40,000	10,000	1,200
1975-1985	30,000	3,000	2.2	1.5	2	30,000	5,000	1,000
1965-1975	30,000	4,000	2.0	1.5	3	20,000	5,000	800
1955-1965	20,000	5,000	2.0	1.5	4	20,000	5,000	500

(ii) RAINFED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	190,000	5,000	1.6	1.1	2	100,000	20,000	20
1985-1995	70,000	6,000	1.5	1.0	2	40,000	5,000	1,000
1975-1985	60,000	6,000	1.3	0.7	2	30,000	5,000	800
1965-1975	50,000	7,000	1.3	0.6	1	20,000	3,000	500
1955-1965	40,000	8,000	1.3	0.6	2	20,000	3,000	500

Dominating varieties: Jagger, Steklovidnaya 24, Atoy, Sulton 95
Dominating landraces: Safedak, Surkhak

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

(i) IRRIGATED AREAS

2 yr period	Conventional tillage *hectares sown*	Reduced/zero tillage *hectares sown*	Average N:P:K applied *kg/ha*	Fully mechanized *% of area*	Sown on flat *hectares sown*	Sown on raised beds *hectares sown*	Gravity:sprinkler irrigation *ratio*	Irrigation applied *mm or frequency*
2004-2005	120,000	0	300	100		120,000	100:00:00	3
2002-2003	115,000	0	200	100		115,000	100:00:00	3
2000-2001	125,000	0	200	100		125,000	100:00:00	3
1998-1999	120,000	0	200	100		120,000	100:00:00	3
1996-1997	110,000	0	200	100		110,000	100:00:00	3

(ii) RAINFED AREAS

2 yr period	Conventional tillage *hectares sown*	Reduced/zero tillage *hectares sown*	Average N:P:K applied *kg/ha*	Fully mechanized *% of area*	Annual *cropping*	Weed *control*	Broad leaf weeds *(grasses)*
2004-2005	210,000	0	200	Estimated	210,000	Manually	Manually
2002-2003	195,000	0	200	Estimated	195,000	Manually	Manually
2000-2001	215,000	0	200	Estimated	215,000	Manually	Manually
1998-1999	210,000	0	200	Estimated	210,000	Manually	Manually

Table 3. Current and emerging constraints to wheat production

Environmental constraint	YES/NO	Description of constraint	Area affected	Typical yield loss
Abiotic			*hectares or % of total area*	*range (%)*
Low rainfall	Yes	Drought every 4-5 years	30%	40-50%
Declining water resources (for irrigation)	Yes	Irrigation infrastructure deteriorated	40%	40%
Heat				
Cold				
Salinization				
Soil physical degradation				
Micro-element deficiency (e.g., Zn, Bo)		No study conducted		
Micro-element toxicity (e.g., Al, Bo)		No study conducted		
Lodging				
Other				
Biotic				
Diseases	Yes	Yellow rust, tan spot, bunt	30%	30%
Pests	Yes	Aphids, sun bug, may bug (in rainfed zone)	20%	20%
Weeds				
Socioeconomic constraint				
Credit	Yes	Banks do not want to provide credit to an agricultural sector, except cotton	100%	
Seed availability/quality	Yes	Seed industry totally collapsed, private seed farms starting to act	100%	
Fertilizer availability	Yes	Fertilizer price is high and quality is low - no control on quality	100%	
Fungicide/pesticides/herbicides availability/cost	Yes	The price is not affordable, no control of quality which is low	100%	
Mechanization/access to suitable machinery	Yes	Farm machinery rundown	100%	
Labor	No	There is an excess of labor	100%	
Transport	Yes	Difficult to transport	100%	
Grain price/ marketing	Yes	Seasonal fluctuation of price	100%	
Conflict with other crop or livestock systems	Yes	Government is interested in growing cotton, but farmers, wheat	50%	

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	YES/NO	Description of constraint	Priority (Highest, high, moderate, low, not)	Approx investment required $
Field station operations (budget, land, staff, etc.)	Yes	Low budgets for research and low salaries	High	200,000
Field machinery	Yes	Field machinery is rundown	High	500,000
Technical assistance staff	No	Sufficient	Not	
Scientific expertise (genetics, pathology, agronomy, etc.)	Yes	Lack of good specialists, generation gap, young people do not into research	Highest	
Socioeconomic expertise (market & impacts analysis, etc.)	Yes	Market studies is a new subject and not well studied	High	50,000
Labs/instruments (e.g., quality LAB, MAS, driyers, etc.)	Yes	Labs are not modernized, there are not sufficient equipment, spare parts, chemicals, etc.	High	300,000
Computers/software/GIS	Yes/No	There are some computers provided by the projects, but no modern software	High	50,000
Controlled growth environments	Yes	No greenhouses	High	50,000
Access to genetic resources/storage	No	Receive germplasm from CIMMYT and ICARDA, national gene bank is established	Moderate	
Training resources (classrooms, etc.)	No	There are sufficient resources for conducting trainings	Moderate	
Transport	Yes	Transport only for administration, not for researchers	High	50,000
Resources to support collaboration & information sharing	Yes	No local network and no access to internet	High	50,000
Other				
		TOTAL		**1,250,000**

Table 5. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance *1-6**	Example of partnership *Optional*
Farmer groups	2	
Local private companies	1	
International centers	3	
Foreign research institutions	4	
Multinationals	5	
NGOs	6	

* Ranking (1=most important, 6=least important)

Table 6. Most useful /desirable outputs from CGIAR centers

CIMMYT Output	Specify	*Priority (Highest, high, moderate, low, not)*
Germplasm		
Advanced lines with generic traits (yield, disease res., etc.)	CIMMYT is the main source of advanced lines for the National Breeding Programmes	Highest
Segregating bulks (F2 onwards)		
Genetic resources		
Training/knowledge sharing		
Basic training for younger scientists	2 researchers took wheat training and 2 took a course on bed planting, but still there is an urgent need for trainings due to generation gap	Highest
Advanced courses for mid-career scientists		High
Specialized visits of individual scientists, e.g., to CIMMYT	Visiting CIMMYT, familiarization with activities and conducting cooperative research provides more chances for development of wheat breeding	High
Visits of CIMMYT scientists to your program	From each visit of CIMMYT researchers we learn a lot	Highest
Methodologies/Information/Publications on		
Breeding (e.g., international nursery reports; IWIS, etc.)		High
Pathology and pest control	Developed methodology and publications on pathology and pest control are very useful	High
Genetics (quantitative and molecular)		
Pre-breeding and genetic resources		
Physiology (crop and/or cellular)		
Statistics and experimental design	Researchers are familiar with statistics but do not apply	High
Crop management	Especially bed and zero-till technology	High
Participatory methods	It is very new for Tajikistan	Moderate
Seed technolgy	Seed science should be developed	High
Social science and economic analysis	Economic analysis has been done to find areas that should be supported	High
Training methods		
Software support for databases, GIS, websites, etc.		

Wheat in Turkey

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Turkey is among the 10 biggest wheat producers worldwide. Total wheat production of Turkey varies between 16 and 21 million tons, including 4–6 million tons of durum wheat. Around 65–70 % of the total arable land area of 27 million ha is devoted to cereal production of which wheat (9.5m ha), barley (3.5m ha) and annual fallow (5–6.5m ha) predominate. About 80-90% of all wheat in Turkey is produced under rainfed conditions. Winter and facultative wheat account for about 6 million ha and 60-70 % of the production. The average grain yield of 2 t ha^{-1} conceals wide disparities in production potential due to extremely diverse agro-ecological conditions and varies from 1 t ha^{-1} in the winter wheat areas of Eastern-Turkey to 3.5-4.5 t ha^{-1} in Thrace (European part of Turkey) and South-Turkey. Since 1967 Turkey has released 138 cultivars: 42 spring bread wheat, 24 spring durum wheat, 58 winter bread wheat and 14 winter durum wheat.

In the irrigated areas the majority of wheat is sown on flat but there is an increasing interest among farmers to adopt bed planting technologies. Likewise, most of the wheat in rainfed areas is grown using conventional tillage systems, although farmers who have been exposed to zero-tillage systems through farmer field days organized by the Research Institutes have shown great interest in this technology.

The main abiotic constraints for wheat production is drought due to low rainfall which can affect up to 80% of the total area and degradation of the soil structure due to excess soil tillage which can affect up to 70% of the total area. Other important constraints, but present in specific areas or years are heat, Zn and Bo deficiency, toxicity to certain micro elements, and lodging due to heavy rain. Major biotic constraints are yellow rust, leaf rust, and soil borne diseases and nematodes, while Suny bug and Zabrus are the most devastating pests. Of socioeconomic constraints, main problems are the lack of credit and high interest rates, together with distribution problems of high quality certified seed.

Main constraints for wheat improvement activities are a general shortage of research budget and an erosion of senior staff and scientific expertise due to lack of incentives, a lack of socio economic expertise, and a general need to update the information system to improve collaboration and data sharing.

Farmer groups remain the most important partner to achieving national wheat program goals, although the international centers, and particularly the Turkey-CIMMYT-ICARDA Winter Wheat Improvement Program (IWWIP), and to a lesser extent local private companies, remain important research partners.

The outputs of highest importance from collaboration with the CGIAR research centers are access to advanced lines with high yield potential, disease resistance and quality and the opportunity for younger scientist to receive basic training in plant breeding and agronomy. Other high valued outputs are the advanced courses for mid career scientists, access to information generated by the IWIS, and access to information and collaboration in particularly molecular technologies, pathology and physiology.

Turkey

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Table 1a. Winter wheat cultivars grown and released in irrigated and rainfed areas, 1955-present

(i) IRRIGATED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	1,200,000	0	3.5-4.5		22	300,000	200,000	2
1985-1995	900,000	0	3-4		5	500,000	200,000	2
1975-1985	500,000	0	3		4	300,000	200,000	2.2
1965-1975	300,000	0	2.5		4	250,000	100,000	2
1955-1965	50,000	0	2		0	200,000	100,000	1

(ii) RAINFED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	4,700,000	500,000	1.8	1.5	21	1,200,000	1,000,000	4.5
1985-1995	4,700,000	800,000	1.7	1.5	5	1,400,000	900,000	5
1975-1985	3,100,000	1,200,000	1.5	1.5	3	1,500,000	900,000	7
1965-1975	2,800,000	2,000,000	1.4	1	3	1,500,000	600,000	6
1955-1965	2,200,000	2,000,000	1	0.8	2	1,020,000	150,000	4

Table 1b. Spring wheat cultivars grown and released in irrigated and rainfed areas, 1955-present

(i) IRRIGATED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	250,000	0	3.5-4.5	-		100,000	25,000	2
1985-1995	100,000	0	3.0-4.0	-		50,000	15,000	2
1975-1985	50,000	0	2.5-3.5	-		20,000	5,000	1.5
1965-1975	0	0	-	-		0		0
1955-1965	0	0	-	-		0		0

(ii) RAINFED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	2,500,000	200,000	2.5	1.5	37	200,000	70,000	5
1985-1995	2,300,000	550,000	2.3	1.5	26	150,00	70,000	5
1975-1985	3,600,000	600,000	2.1	1.5	17	60,000	30,000	5
1965-1975	2,500,000	1,000,000	2	1	4	70,000	20,000	5
1955-1965	2,000,000	1,300,000	1.15	0.8	0	80,000	10,000	5

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

(i) IRRIGATED AREAS

2 yr period	Conventional tillage hectares sown	Reduced/zero tillage hectares sown	Average N:P:K applied kg/ha	Fully mechanized % of area	Sown on flat hectares sown	Sown on raised beds hectares sown	Gravity:sprinkler irrigation ratio	Irrigation applied mm or frequency
2004-2005	1,450,000	0	150:80:0	100%	1,450,000	500	%15 sprinkler,%85 flood irrigation	1 or 2
2002-2003	1,450,000	0	150:80:0	100%	1,450,000	200		1 or 2
2000-2001	1,200,000	0	150:80:0	100%	1,200,000	10		1 or 2
1998-1999	1,150,000	0	150:80:0	100%	1,150,000	0		1 or 2
1996-1997	1,150,000	0	150:80:0	100%	1,150,000	0		1 or 2

(ii) RAINFED AREAS

2 yr period	Conventional tillage hectares sown	Reduced/zero tillage hectares sown	Average N:P:K applied kg/ha	Fully mechanized % of area	Annual cropping hectares sown	Cereal-fallow hectares sown	Weed control (grasses) methods	Broadleaf weeds methods
2004-2005	7,900,000	1,000	80:60:0	90	5,600,000	2,300,000	Chemical	Chemical
2002-2003	7,900,000	1,000	80:60:0	88	5,400,000	2,500,000	Chemical	Chemical
2000-2001	8,150,000	1,000	80:60:0	85	5,600,000	2,550,000	Chemical	Chemical
1998-1999	8,100,000	0	80:60:0	82	5,800,000	2,300,000	Chemical	Chemical
1996-1997	8,100,000	0	80:60:0	80	5,700,000	2,400,000	Chemical	Chemical

Table 3. Current and emerging constraints to wheat production

Environmental constraint	Yes/No	Description of constraint	Area affected (potential)	Typical yield loss
Abiotic			Hectares or % of total area	Range (%)
Low rainfall	Yes	Yearly fluctuation and seasonal distribution	80%	20-50%
Declining water resources (for irrigation)	Yes	In some years	20%	50-60%
Heat	Yes	In some years in irrigated areas	20%	20-30%
Cold	No	Varieties are resistant		
Salinization	No	Only on small local areas		
Soil physical degradation	Yes	Due to heavy use of discplows	70%	?
Micro-element deficiency (e.g., Zn, Bo)	Yes	Zn deficiency in dry years	15-20%	30-35%
Micro-element toxicity (e.g., Al, Bo)	Yes	Boron toxicity in local areas	5-10%	15-20%
Lodging	Yes	Especially heavy rain and excessive irrigation		
Other				
Biotic				
Diseases	Yes	Yellow rust, leaf rust, stem rust	50%	20-30%
Pests	Yes	Suny bug, zabrus spp.	50-60%	5-30%
Weeds	Yes	Circium arvense, Avena fatua, Galium aparina, Boreava oriantalis, Bromus spp.	30-50%	5-10%
Socioeconomic constraint				
Credit	Yes	High interest rates		
Seed availability/quality	Yes	Distribution problems		
Fertilizer availability	No			
Fungicide/pesticides/herbicides availability/cost	No			
Mechanization/access to suitable machinery	Yes	No problem related to access but traditions prevail		
Labor	No			
Transport	No			
Grain price/ marketing	No			
Conflict with other crop or livestock systems	No			

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	Yes/No	Description of constraint	Priority	Approx investment required $
Field station operations (budget, land, staff, etc.)	Yes	Shortage of research budget and technical staff	High	
Field machinery	Yes	Low number and old machinery	Moderate	
Technical assistance staff	Yes	Not well trained or dedicated	Moderate	
Scientific expertise (genetics, pathology, agronomy, etc.)	Yes	Shortage of senior staff due to lack of incentives	High	
Socioeconomic expertise (market & impacts analysis, etc.)	Yes	Lack of monitoring and evaluation	High	
Labs/instruments (e.g., quality LAB, MAS, dryers, etc.)	Yes	In some institutions	Moderate	
Computers/software/GIS	No			
Controlled growth environments	Yes	Not properly used	Moderate	
Access to genetic resources/storage	No			
Training resources (classrooms, etc.)	Yes	Not well organized in place and in number	Moderate	
Transport	Yes		Moderate	
Resources to support collaboration & information sharing	Yes	Need more electronic/net system for sharing outputs and information	High	
Other				

Table 5. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance 1-6*	Example of partnership Optional
Farmer groups	1	
Local private companies	3	
International centers	2	Turkey/CIMMYT/ICARDA International Winter Wheat Improvement Program
Foreign research institutions	5	
Multinationals	6	Not involved in wheat research or seed sales
NGOs	4	

* Ranking (1=most important, 6=least important)

Table 6. Most useful /desirable outputs from CGIAR centers

CIMMYT output	Specify	Priority
Germplasm		
Advanced lines with generic traits (yield, disease res., etc.)	Yield potential, disease resistance, quality	Highest
Segregating bulks (F2 onwards)		Moderate
Genetic resources	Yield potential, disease resistance, biotic stress tolerance, quality	Low
Training/knowledge sharing		
Basic training for younger scientists	Breeding, agronomy	Highest
Advanced courses for mid-career scientists	Germplasm development, biotechnology (molecular marker techniques)	High
Specialized visits of individual scientists, e.g., to CIMMYT	Target oriented related to specific projects	Moderate
Visits of CIMMYT scientists to your program	Especially joint agronomy and pathology research	Moderate
Methodologies/Information/Publications on		
Breeding (e.g., international nursery reports; IWIS, etc.)		High
Pathology and pest control		High
Genetics (quantitative and molecular)	Molecular genetics for disease resistance	High
Pre-breeding and genetic resources		Moderate
Physiology (crop and/or cellular)	Crop physiology	High
Statistics and experimental design		Moderate
Crop management		Moderate
Participatory methods		Moderate
Seed technology		Low
Social science and economic analysis		High
Training methods		Moderate
Software support for databases, GIS, websites, etc.		Low

An Overview of Agriculture in Uzbekistan

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The country has total area of 44.8 mln hectares, but only 4.5 mln hectares are arable; 4 mln are irrigated. Agriculture provides approximately 40% of GNP. It has a population of 26.8 mln people growing at 2.20% per year. Agriculture plays an important role in the economy contributing 38% to the GDP and employing 44% of the population. The main strategic crops (80% irrigated area) cotton and winter wheat. Fruits, potato and vegetables are also important crops. During the first six years of independence, the area under cotton was reduced from 2 to 1.5 mln hectares and replaced by grain production. As a landlocked country with limited access to international markets, food security is of paramount significance. Since independence, wheat has become second in importance to cotton. In order to attain food security, wheat area under irrigation increased over the years, currently at 1.3 mln hectares including rainfed production. This increase in cultivated areas stimulated the use of modern production approaches in the national wheat program. Uzbekistan is now selfsufficient in grain production. The average yield of wheat is 4.2 tones per hectare, which is almost three times higher than in 1994. Annual average wheat grain production has reached up to 6 mln tones. In view of increasing of human population, changes in agronomic and economic conditions Uzbekistan is facing the necessity of further increasing of grain production. The reserves for that are in development of new high yielding varieties, tolerant to diseases and with good baking qualities. Taking into consideration that varieties, developed in Uzbekistan, are more suitable to local conditions, therefore, own breeding in seed production should be given a high priority. In view of drastic changes in economy (90% of land in private hands) new approaches in seed production must be elaborated to meet requirements of private sector. As for strategic crops of cotton and wheat, these innovations should be taken step by step. For other crops, market relations should be applied in the nearest future.

Uzbekistan

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Table 1. Cultivars grown and released in irrigated and rainfed areas, 1955-present

(i) IRRIGATED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	1,086,000	0	3.7		37	356,000	278,000	40
1985-1995	–	–						
1975-1985	–	–						
1965-1975	–	–						
1955-1965	–	–						

(ii) RAINFED AREAS

Period	Modern varieties (MV) *hectares sown*	Landraces *hectares sown*	Avg MV yield *t/ha*	Avg landrace yield *t/ha*	Cultivars released *number*	Dominant variety 1 *hectares sown*	Dominant variety 2 *hectartes sown*	Avg farm size *ha*
1995-2005	286,000	0	1.1	0.8	8	90,000	75,000	200
1985-1995	–	–						
1975-1985	–	–						
1965-1975	–	–						

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

(i) IRRIGATED AREAS

2 yr period	Conventional tillage hectares sown	Reduced/zero tillage hectares sown	Average N:P:K applied kg/ha	Fully mechanized % of area	Sown on flat % of area	Sown on raised beds hectares sown	Gravity:sprinkler irrigation ratio	Irrigation applied mm or frequency
2004-2005	1,086,000	40	165/80	100	1,086,000	100	1:00	2,000
2002-2003	1,055,000	15	155/70	100	1,055,000	36	1:00	2,000
2000-2001	1,000,000	2	145/60	100	1,000,000	15	1:00	2,000
1998-1999	1,100,000	0	146/55	100	1,100,000	0	1:00	2,000
1996-1997	987,000	0	130/55	100	987,000	0	1:00	2,000

(ii) RAINFED AREAS

2 yr period	Conventional tillage hectares sown	Reduced/zero tillage hectares sown	Average N:P:K applied kg/ha	Fully mechanized % of area	Annual cropping hectares sown	Cereal-fallow % area	Weed control (grasses) methods	Broadleaf weeds methods
2004-2005	286,000	12	65/60	100	286,000	75/25	Herbicides	Herbicides
2002-2003	240,000	5	55/50	100	240,000	62/38	Herbicides	Herbicides
2000-2001	176,000	1	45/40	100	176,000	46/54	Herbicides	Herbicides
1998-1999	240,000	0	43/40	100	240,000	62/38	Herbicides	Herbicides
1996-1997	286,000	0	30/35	100	286,000	75/25	Herbicides	Herbicides

Table 3. Current and emerging constraints to wheat production

Environmental constraint	YES/NO	Description of constraint	Area affected (potential)	Typical yield loss
Abiotic			***Hectares or % of total area***	***Range (%)***
Low rainfall	Yes	In some areas of precipitation is lower than 350 mm, sometimes as low as 80mm	15%	20-50
Declining water resources (for irrigation)	Yes	About half of the area of Uzbekistan is reduced irrigated	50%	15-40%
Heat	Yes	During the grain filling period of wheat, the temperature can go up to 40°C	40%	10%
Cold	Yes	During winter time sometimes the temperature goes down to -25-30°C	20%	5%
Salinization	Yes	In Uzbekistan about 2 million ha suffer from salinity problems	50%	25 %
Soil physical degradation	Yes	Water and wind erosion	40%	5%
Micro-element deficiency (e.g., Zn, Bo)	Yes	Zn deficiency is most crucial problem in rainfed area of Uzbekistan	40%	5 %
Micro-element toxicity (e.g., Al, Bo)	No			
Lodging	Yes	Irrigation lodging is the main problem	35%	15%
Other				
Biotic				
Diseases		Yellow, brown, and powdery mildew		
		Some years yellow rust can damage up to 30% of yield		30%
Pests		Sun pest		
		Quality of wheat is low		5%
Weeds		Weeds are reducing yield up to 5%		5%
Socioeconomic constraint				
Credit	Yes	There is no low interest credit		
Seed availability/quality	No	Seeds are controlled by the Government		
Fertilizer availability	No	Government is taking care of it		
Fungicide/pesticides/herbicides availability/cost	No	Government is taking care of it		
Mechanization/access to suitable machinery	No	Government is taking care of it		
Labor	No	Government is taking care of it		
Transport	No	Government is taking care of it		
Grain price/ marketing	No	Government is taking care of it		
Conflict with other crop or livestock systems	No	Government is taking care of it		

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	YES/NO	Description of constraint	*Priority (Highest, high, moderate, low, not)*	Approx investment required $
Field station operations (budget, land, staff, etc.)	Yes	Financial problems	Highest	450,000
Field machinery	Yes	Financial problems	Highest	2,000,000
Technical assistance staff	No			
Scientific expertise (genetics, pathology, agronomy, etc.)	No			
Socioeconomic expertise (market & impacts analysis, etc.)	Yes	Socioeconomic study is not supported by sufficient expertise	Highest	1,000,000
Labs/instruments (e.g., quality LAB, MAS, dryers, etc.)	Yes	There are urgent needs for lab equipment. All equipment left from former USSR	Highest	1,500,000
Computers/software/GIS	No			
Controlled growth environments	Yes			147,563
Access to genetic resources/storage	No			
Training resources (classrooms, etc.)	No			
Transport	Yes	No cars available for transport	Highest	10,000,000
Resources to support collaboration & information sharing	Yes	Information sharing is not well develop	Highest	1,200,000
Other				

Table 5. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance 1-6*	Example of partnership Optional
Farmer groups	1	90% of lands in now privatized
Local private companies	2	Local private companies have been estabilished recently
International centers	1	International centers are function well
Foreign research institutions	2	Some foreign research institute are coming to Uzbekistan slowly
Multinationals	3	
NGOs	4	NGOs are not fucntioning well in Uzbekistan

* Ranking (1=most important, 6=least important)

Table 6. Most useful/desirable outputs from CGIAR centers

CIMMYT output	Specify	Priority (Highest, high, moderate, low, not)
Germplasm		
Advanced lines with generic traits (yield, disease res, etc.)	High yielding, resistant to disease and drought	Highest
Segregating bulks (F2 onwards)		High
Genetic resources	Each year more than 2,000 accessions are received	High
Training/knowledge sharing		
Basic training for younger scientists	Young scientists have received English and other training courses with support of CIMMYT	Highest
Advanced courses for mid-career scientists		
Specialized visits of individual scientists, e.g., to CIMMYT	Four young scientists received training in CIMMYT	High
Visits of CIMMYT scientists to your program	Highly appreciated	High
Methodologies/Information/Publications on		High
Breeding (e.g., international nursery reports; IWIS, etc.)	We have received books	High
Pathology and pest control	Each year we have been introduced to some training courses where we learned about new methods related to this issue.	Highest
Genetics (quantitative and molecular)		High
Pre-breeding and genetic resources		High
Physiology (crop and/or cellular)		High
Statistics and experimental design		High
Crop management		High
Participatory methods		High
Seed technolgy		High
Social science and economic analysis		High
Training methods		High
Software support for databases, GIS, websites, etc.		High

Wheat Production Constraints in Zimbabwe

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Rainfed wheat production in Zimbabwe has been attempted and failed due to high humidity, high day and night temperatures, disease and weed proliferation during the summer and autumn month in this Tropical Country (Rattray, 1969). The country thus depends irrigated spring wheat grown during the winter months within the calender window, May to mid - November.

The yield potential of irrigated wheat in Zimbabwe is highly dependant on temperature as affected by altitude (Cacket and Wall 1971; Mashiringwani, 1985). Temperature has a marked effect on season length yield and hecto- litre mass. The yield potential of wheat in the highveld (>1200m) ranges from 6 to 10 t/ ha.

In contrast, the yield potential in the lowveld (< 800 m) is in the range 4 to 6.5 t /ha because the crop experiences high temperatures at both ends of the growing cycle and sometimes suffers frost damage at flowering and during early grain fill. High temperatures reduce potential grain number and size (Cacket and Wall, 1971), leading to a reduction in yield potential.

Another major yield constrain in irrigated wheat crop in Zimbabwe is the limited irrigation water resource i.e. dam water distribution and capacities, as influenced by erratic rainfall and limited development capacity in the country (Mashiringwani and Harawa 1985 Associated with the problem is the limited irrigation management capacity of the farmers which has worsened in the recent land reform exercise which substituted the experience farmers with the inexperienced and resource poor ones. Electricity supply problems water pump and delivery systems shortages and breakdowns are also aggravating.

Timely planting of wheat crop to maximise yield potential is now difficult due to shortage of machinery, timeouts crop chemicals and wheat seed delivery and crop rotational problems.

Disease pressure increases from the highveld region (>1200m) to the lowveld region (400 - 800m). Leaf rust (*Puccina recondita tritici*), stem rust (*Puccinia graminis tritici*) and powdery mildew (*Erysiphe graminis tritici*) are the major disease threats to wheat production in Zimbabwe. Of late *Alternaria* pathotype which has not yet been characterised is of major concern. *Quelea* birds, aphids and ball worms cause sporadic damage on wheat crop in Zimbabwe as well. Pre-harvest sprouting damage destroyed the Zimbabwe wheat crop in 1995 and is a threat to late planted crops.

CIMMYT deserves strong acknowledgement as the basic resource for high yielding agronomically adapted germplasm in wheat improvement in Zimbabwe. The genetic yield potential of cultivars has improved steadily at 1.2 percent / year from 1969 to 1991 (Mashringwani, 1993) and has been maintained at +/- 0.5 percent / year up to 2005.

Zimbabwe

E. K. Havazvidi, Seed Co Limited

Table 1. Cultivars grown and released in irrigated and rainfed areas, 1955-present

	(i) IRRIGATED AREAS							
Period	Modern varieties (MV) hectares sown	Landraces hectares sown	Avg MV yield t/ha	Avg landrace yield t/ha	Cultivars released number	Dominant variety 1 hectares sown	Dominant variety 2 hectartes sown	Avg farm size ha
1995-2005	50,000	0	7	0	10	25,000	20,000	100
1985-1995	45,000	0	6	0	8	20,000	15,000	100
1975-1985	37,800	0	5	0	6	20,000	10,000	100
1965-1975	17,000	0	4	0	1	17,000		50
1955-1965	8,000	0	3	0	1	8,000		10

Table 2. Summary of agronomic practices, irrigated and rainfed areas, 1996-2005

	(i) IRRIGATED AREAS							
2 yr period	Conventional tillage hectares sown	Reduced/zero tillage hectares sown	Average N:P:K applied kg/ha	Fully mechanized % of area	Sown on flat hectares sown	Sown on raised beds hectares sown	Gravity:sprinkler irrigation ratio	Irrigation applied mm or frequency
2004-2005	35,000	7,000	300	70	42,000	0	2:98	300
2002-2003	30,000	7,000	400	70	37,000	0	2:98	300
2000-2001	30,000	20,000	450	100	50,000	0	2:98	500
1998-1999	30,000	20,000	450	100	50,000	0	2:98	500
1996-1997	30,000	20,000	450	100	50,000	0	2:98	500

Table 3. Current and emerging constraints to wheat production

Environmental constraint	YES/NO	Description of constraint	Area affected	Typical yield loss
Abiotic			hectares or % of total area	range (%)
Low rainfall	No			
Declining water resources (for irrigation)	Yes	Erratic rainfall 200mm to 800mm, low dam capacities in low rainfall years	40-70% of 60,000 ha	30-60%
Heat	Yes	Maximum daily temperatures usually above 25°C required for optimal growth	60-80%	30-60%
Cold	Yes	Sporadic frost damage	5-10%	5-10%
Salinization	No			
Soil physical degradation	No			
Micro-element deficiency (e.g., Zn, Bo)	Yes	Low pH conditions induce trace element deficiencies and toxicities	20-30%	5-10%
Micro-element toxicity (e.g., Al, Bo)	Yes	Low pH conditions induce trace element deficiencies and toxicities	20-30%	5-10%
Lodging	Yes	Poor crop management and weak straw strength in some varieties	20-30%	10-20%
Other				
Biotic				
Diseases	Yes	P.recondita and P.graminis (rusts) and powdery mildew (E. graminis tritici)	20-50%	20-50%
Pests	Yes	Quelia birds, aphids and bollworms	20-40%	20-30%
Weeds	Yes	Broadleaves	30-60%	10-20%
Socioeconomic constraint				
Credit	Yes	Limited loan facilities	60-80%	50-80%
Seed availability/quality	No			
Fertilizer availability	Yes	Limited fertilizer availability	60-80%	50-70%
Fungicide/pesticides/herbicides availability/cost	Yes	Limited mechanization capacity	50-60%	20-30%
Mechanization/access to suitable machinery	Yes	Limited mechanization capacity	70-90%	50-60%
Labor	No			
Transport	No			
Grain price/marketing	Yes	High inflation in Zimbabwe	100%	60-70%
Conflict with other crop or livestock systems	No			

Table 4. Current and emerging constraints to wheat improvement activities

Constraint	YES/NO	Description of constraint	Priority *(Highest, high, moderate, low, not)*	Approx investment required $
Field station operations (budget, land, staff, etc.)	Yes	Limited funding of research	High	10,000
Field machinery	Yes			
Technical assistance staff	Yes	One breeder	High	5,000
Scientific expertise (genetics, pathology, agronomy, etc.)	Yes	Absence of doubled haploid technology	High	20,000
Socioeconomic expertise (market & impacts analysis, etc.)	No			
Labs/instruments (e.g., quality LAB, MAS, dryers, etc.)	Yes	Lack of infrastructure and expertise	Moderate	5,000
Computers/software/GIS	No			
Controlled growth environments	No			
Access to genetic resources/storage	No			
Training resources (classrooms, etc.)	No			
Transport	Yes	Limited logistics	High	10,000
Resources to support collaboration & information sharing	Yes	Government pricing policy	Low	
Other				

Table 5. Relative importance of research partnerships to achieving national wheat program goals

Collaborative partners	Importance 1-6*	Example of partnership Optional
Farmer groups	4	
Local private companies	4	
International centers	2	
Foreign research institutions	1	
Multinationals	3	
NGOs	3	

* Ranking (1=most important, 6=least important)

Table 6. Most useful /desirable outputs from CGIAR centers

CIMMYT Output	Specify	Priority *(Highest, high, moderate, low, not)*
Germplasm		
Advanced lines with generic traits (yield, disease res., etc.)	ESWYT, IBWSN, ISWYN	High
Segregating bulks (F2 onwards)	Irrigated spring wheat F2 ME1	High
Genetic resources		
Training/knowledge sharing		
Basic training for younger scientists	Yes. One successor	High
Advanced courses for mid-career scientists		
Specialized visits of individual scientists, e.g., to CIMMYT	Yes. Dr E.K. Havazvidi at least once in 3 years to visit CIMMYT Obregon to select germplasm	High
Visits of CIMMYT scientists to your program	Yes. At least once in 5 years CIMMYT scientists to visit RARS and Zimbabwe	High
Methodologies/Information/Publications on		
Breeding (e.g., international nursery reports; IWIS, etc.)	Yes. RARS submits CIMMYT nursery returns every year	High
Pathology and pest control	Alternaria disease spreading in Zimbabwe; pathologists requested from CIMMYT to advise	High
Genetics (quantitative and molecular)		
Pre-breeding and genetic resources	Doubled haploid technology back up from CIMMYT is vital	High
Physiology (crop and/or cellular)		
Statistics and experimental design	Yes. Near neighbor analysis, augmented designs, AMMI and GxE analysis	High
Crop management		
Participatory methods		
Seed technolgy		
Social science and economic analysis		
Training methods		
Software support for databases, GIS, websites, etc.	Yes. GIS and website information are important	High

Wheat Yield Potential

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Summary

This paper reviews efforts conducted over the last 50 years to increase yield potential gains while improving adaptation to biotic and abiotic stresses. While percent gains have been similar in irrigated and rainfed areas in absolute figures, productivity has increased considerably more in irrigated areas. The authors underscore the need to develop new germplasm with adaptation to abiotic stresses without sacrificing yield potential, so that farmers benefit in favorable years. A good example is Attila, a line that has been reselected or released in countries with highly contrasting environments. They also emphasize the importance of introducing new genetic diversity. For example, results from Wheat International Nurseries distributed by CIMMYT have shown that cultivars with 1B/1R are better adapted to lower input conditions, and other translocations such as 1A/1R, 7DL/7AG have already shown beneficial effects on yield potential in a range of genetic backgrounds.

Introduction

Wheat is a very important commodity worldwide. It is grown on roughly 200 million hectares with an average total production of 600 million metric tons. Global average productivity is around 2.7 t/ha^{-1} with high variability among countries and regions. The highest average yields are obtained in Western Europe, with more than 8 t ha^{-1}, in contrast to less than 1 t ha^{-1} in several countries in Central/West Asia and North Africa (CWANA).

Table 1 lists the wheat area in different regions of the world. The single largest region is CWANA with 52 million hectares, followed by North America with 40 million, South Asia with 37 million, Eastern Europe and Russia with 36 million, East Asia with 29 million, European Union with 17 million, and Australia with 12 million hectares. The largest wheat producing countries are China with 29 million hectares, followed by India with 26 million hectares, and USA with 24 million hectares.

Table 1. Wheat area in different regions of the world.

Geographic region	Area (000 ha)
CWANA (West Asia, North Africa & Central Asia)	52,507
South Asia	36,899
East Asia	28,763
Eastern Europe and Russian Federation	35,963
North America (USA and Canada)	40,043
European Union (EU)	17,322
Australia	12,000
Global	212,000

World demand for wheat by 2020 is estimated at 840 to 1000 million tons. Yield potential and yield gains are essential to meet this demand, as expanding the wheat area is not feasible. Both China and India will be net importers of wheat by 2020 if their average wheat productivity remains stagnant, as it is now in case of India with 2.7 t ha^{-1} in the last six years. The African continent in general is the largest importer of wheat grain, followed by the Middle East and North Africa (MENA). However, some MENA countries, such as Turkey, Syria, Egypt, and Iran, have made splendid progress in wheat production and productivity. The prospect for yield gains in the countries of Central Asia remains high, provided they prioritize research and developmental issues.

Yield Potential: Historical Perspectives

Wheat breeding worldwide in the last 50 years has had many priorities, of which yield potential gains, maintenance of biotic resistance, and increased abiotic tolerance, especially manipulation of traits for drought and heat, have been given a lot of attention. In the last 40 years, many researchers have investigated yield potential gains in wheat (Tables 2 and 3). There have been constant increases in yield potential in many geographic regions of the world, both developed and developing countries. One of the most important breakthroughs was the incorporation of dwarfing genes *Rht1* and *Rht2* in the early 1960s by Dr. N. E. Borlaug and his colleagues. This led to the Green Revolution, especially in the Indian Subcontinent. The genetic gains as a result of international wheat breeding efforts have been spectacular. It is estimated that developing countries in general have benefited due to wheat breading in the order of an additional US$ 3 billion per year (in 1990 US$) (Byerlee and Moya, 1993). These gains are the result of international breeding efforts led by CGIAR centers and NARS.

Past experience has indicated that the gains in percentage have been similar in irrigated and rainfed areas, but in absolute figures grain yield has increased much more in irrigated areas (Table 2 and 3). The Yaqui Valley of Sonora, Mexico, has constantly realized this gain (Figure 1). Trends similar to those in the Yaqui Valley have also been realized in the Punjab (India), Upper Delta (Egypt), Adana region of Turkey, and supplementary irrigated area of Syria. The case of northwestern India is noteworthy: there was a variety shift 10 years ago from a locally bred variety HD2329 to an introduced cultivar Attila from CIMMYT that was released as PBW 343 by Punjab Agricultural University. The variety PBW 343 now occupies 7 million ha in northwestern India (the states of Punjab, Hariyana, Rajasthan, and U.P.). Based on various experiments (unpublished data), yield potential of PBW 343 increased by *ca.* 10% over HD2329. The additional economic returns are in excess of US$ 150 million per year in northwestern India. The variety Attila and its various selections are released and registered in Pakistan, Afghanistan, Iran, Turkey, Algeria, Tunisia, and Morocco. The NARS of these countries released these lines based on yield potential gains in their respective regions.

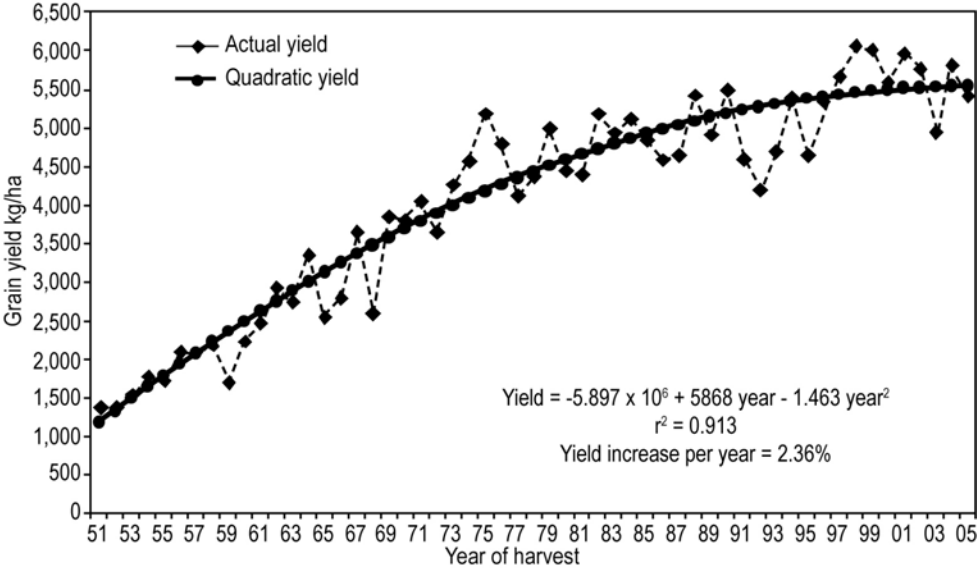
Table 2. Rate of genetic gain in spring bread wheat yield under irrigated conditions.

Environment/ location	Period	Rate of gain (%/year)	Source
Sonora, Mexico	1962-83	1.1	Waddington et al. (1986)
	1962-88	0.9	Sayre et al. (1997)
Nepal	1978-88	1.3	Morris et al. (1992)
India	1967-79	1.2	Kulshreshtha and Jain (1982)
	1989-99	1.9	Nagarajan (2002)
	1996-91	1.0	Jain and Byerlee (1999)
Zimbabwe	1967-85	1.0	Mashiringwani (1987)

Table 3. Rate of genetic gains in spring bread wheat yield under rainfed conditions.

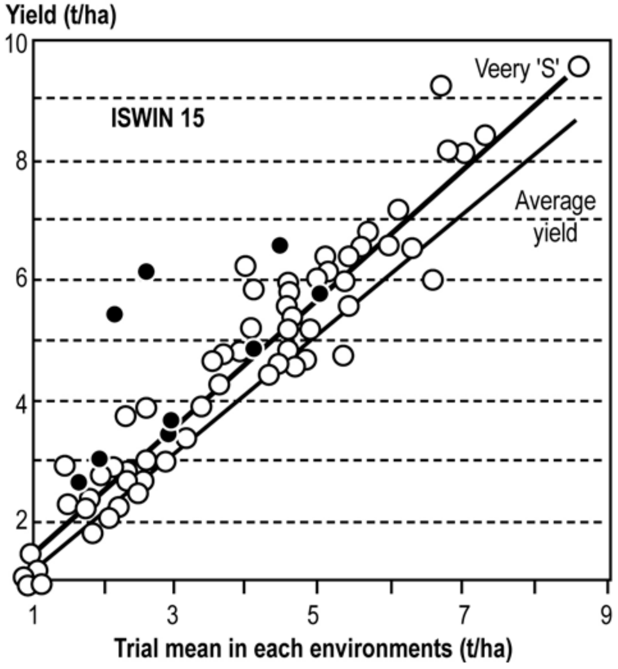
Environment/ location	Period	Rate of gain (%/year)	Source
Ethiopia	1967-94	1.2	Amsal et al. (1996)
Argentina	1966-89	1.9	Byerlee and Moya (1993)
New South Wales (Australia)	1956-84	0.9	Anthony and Brennan (1987)

Figure 1. Wheat yield trend in farmer fields from 1951 to 2005 i the Yaqui Valley of Sonora, México.



The breeding of Attila represents a unique combination of genetic resources from Oregon (USA), France, Mexico (CIMMYT), and India. The original cross was made to combine the yield potential of Veery 5 and the stripe rust resistance of line NdD/P101 from Oregon. Veery 5 had exhibited an outstanding performance in CIMMYT international trials (15th ISWYN) in 73 locations (Figure 2). Its performance in ISWYN 15 was not only excellent in high yielding environments, but superior in poor locations as well. Such cultivars are widely adapted as they combine genes for yield potential with genes needed for adaptation to poor environments. Based on this performance, we developed the hypothesis that varieties can be bred with high yield potential and tolerance to abiotic stresses. The case of Attila proves this hypothesis, as it has been released in countries with contrasting wheat growing environments. The evidence is now emerging that such performance can be also seen in maize hybrids developed in the USA.

Figure 2. Performance of Veery in 73 global environments (ISWYN 15).



Future Research on Yield Potential and Hallmark Germplasm

Rasmusson (1996) proposed the concept of hallmark germplasm in breeding. These germplasm materials are invariably good combiners and show dominant phenotype with positive and useful linkages. Using such lines as parents ensures that the resulting progenies have a high probability for outstanding performance. In the case of bread wheat, Attila and Veery 5 can be classified as hallmark germplasm. At the 7th International Wheat Conference held in Argentina in 2005 several authors presented results related to research on yield potential. Kumari et al. (2005) investigated the variability for stay-green and its association with canopy temperature depression (CTD) and yield traits under terminal heat stress of northeastern India. These authors found a correlation ($r = 0.90$) between LAUD (leaf area under decline) and CTD; LAUD and grainfilling duration ($r = 0.83$); LAUD and grain yield (0.88); and LAUD and biomass ($r = 0.84$). LAUD can be easily used to screen advanced lines. In northeastern India, persistent heat is a major limiting factor for high yield.

CIMMYT researchers Rajaram et al. (1990) were among the first to emphasize the role of the 1B/1R translocation in increasing yield potential in spring wheats. Both Veery and Attilas carry the 1B/1R translocation. Results from International Nurseries distributed by CIMMYT have shown that cultivars with 1B/1R are better adapted to lower input conditions (Figure 2). Foulkes et al. (2005) presented data on wheat varieties from 1972-1995 in the UK and reported a yield potential gain of 1.2% per year. In this study, above-ground biomass and yield were associated with the presence of 1BL/1RS. In a similar study, Zhou et al. (2005) investigated the increase in grain yield for the period from 1970-2000 in the provinces of Hebei, Shandong, and Henan. They reported annual grain yield gains of 0.54%, 0.84%, and 1.05%, respectively, and identified the 1BL/1RS translocation as the main source for this increase in Chinese provinces.

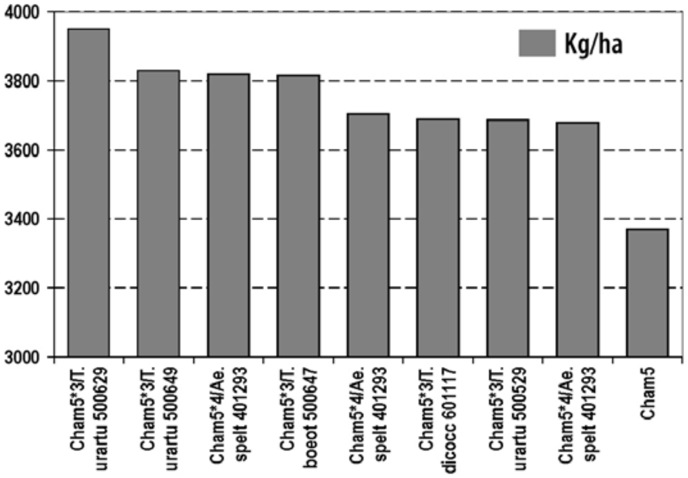
Condon et al. (2005) reported stomatal aperture-related traits to select high yield potential in bread wheats. They proposed that combinations of physiological traits for selection, such as flag leaf stomatal porosity, canopy temperature, carbon isotope discrimination ($\Delta^{13}C$) for photosynthetic capacity, and oxygen isotope ($18_o/16_o$) for stomatal conductance, if applied at the right physiological stage, could result in development of lines with 5-10% higher yield potential. Singh et al. (2005) reported on wheat plants with a changed plant architecture, a kernel weight of 45-50 g, number of grains/spike varying from 90-100, semidwarf plant height (85-100 cm), with dark green broad leaf and robust stems. They identified the line DL1266-5 as having these characteristics; it produced higher yields than PBW 343 at Delhi. This new architectural type has been dubbed super wheat after super rice. CIMMYT researchers have also developed such types, crossing Tetrastichon (from Yugoslavia), Morocco (from Morocco), Agrotriticum (from Canada), Polonicum (tetraploid branched wheat from Poland) with high-yielding parents from CIMMYT's spring wheat program.

To summarize the above research findings, translocations have made major contributions to yield potential in wheat. The role of other translocations such as 1A/1R, 7DL/7AG can be significant, provided they are introduced into cultivars with the right genetic background. The right genetic background is necessary for the positive expression of translocations in regards to yield potential in wheat, since these translocations do not always have positive effects on yield. Figure 3 shows 11 interspecific crosses involving the durum variety Cham 5 with species of *T. urartu*, *Ae. speltoides*, *T. boeticum*, and *T. dicoccoides*. Cham 5 had a yield of 3350 kg ha^{-1} compared to derivatives which had yields from 3650 kg ha^{-1} to 3980 kg ha^{-1} with 300 mm of precipitation. The highest yielding line Cham 5* 3/*T.urartu* 500529 had an 18% higher yield than Cham 5.

Yield Potential and Abiotic Stress Tolerance

In favorable environments, breeding for increased yield potential and biotic stress tolerance/resistance has been the norm for the last 100 years since Mendelian genetics were rediscovered. Breeders have introgressed genes for disease resistance into high yielding and popular cultivars.

Figure 3. Grain yield of lines derived from durum x *Triticum* wild relatives, under limited moisture regime (300 mm of rainfall, 2004). Source: M. Nachit, ICARDA (unpublished).



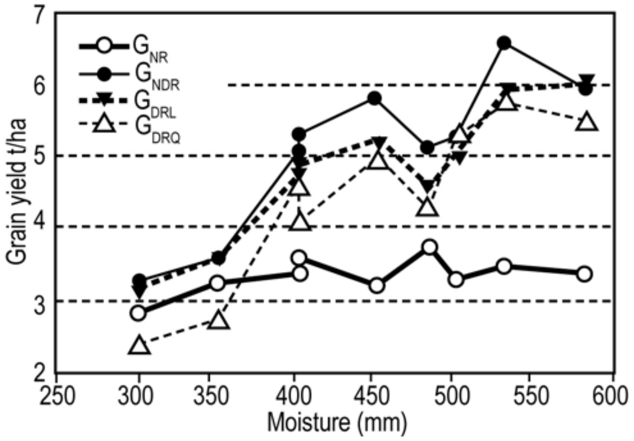
However, the boom and bust cycle of varieties' performance has continued and is continuing; i.e., high yielding cultivars become susceptible to new races and are withdrawn from cultivation to be replaced with resistant ones.

There has not been a parallel phenomenon in relation to combining yield potential and tolerance to drought, heat, and other abiotic environmental stresses. Breeders developing cultivars for abiotic stress environments have mostly ignored yield potential and focused on stress tolerance. However, there is a need for stress tolerant cultivars with high yield potential in years with high rainfall. In such years, tall cultivars lodge, and yields are further reduced due to disease susceptibility. The Mediterranean region's agriculture is not completely rainfed. One or two supplementary irrigations providing an additional 100 mm of water is not uncommon in Turkey, Syria, and many Central Asian countries. In such production systems, it is essential to breed cultivars which possess drought tolerance and yield potential. The breeding methodology needs to address the situation. Veery 5 and Attila are excellent examples of adaptation to supplementary irrigation. The ICARDA-CIMMYT wheat breeding methodology has been designed to address the Mediterranean drought situation. Data presented in Figures 4 and 5 show yield performance of experimental wheat lines under natural rainfed conditions and under supplementary irrigation with additional 100 mm of water.

Figure 4 shows the performance of 25 winter wheats grouped as GNR (non-responsive), GNDR (responsive without drought tolerance), GDRL (linear responsiveness with drought tolerance), and GDRQ (quadratic responsiveness with drought tolerance). The categories GNR and GNDR should not be promoted when there are genotypes of GDRL and GDRQ categories. The GDRL types have higher levels of drought tolerance compared to GNR (traditional varieties) and show higher yield potential compared to GNDR and GDRQ.

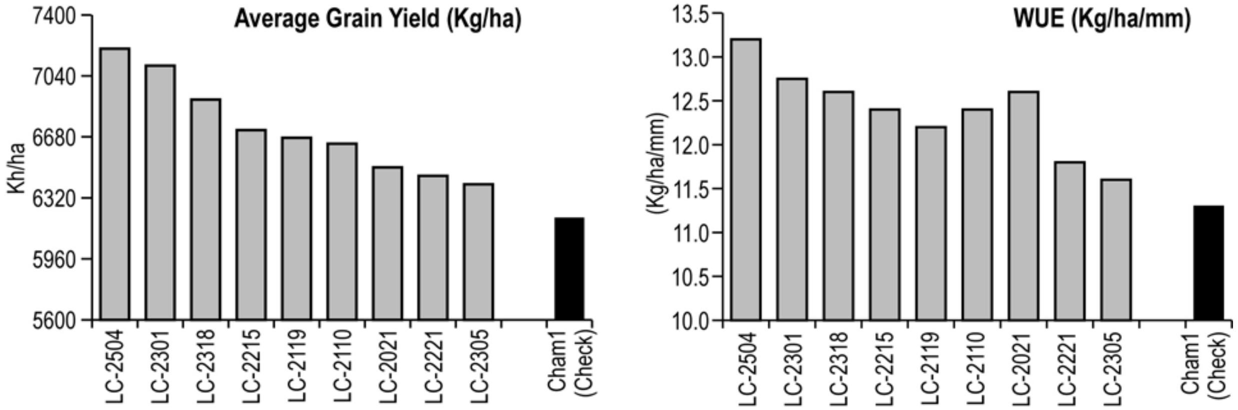
Figure 5 shows the performance of nine new durum lines compared to check variety Cham 1. The experiment was conducted at Aleppo, Syria, ICARDA, under two water regimes. The graphics give yield and water use efficiency in terms of kg/ha/mm. The variety LC 2504 was not only the highest yielding, but also had highest value for water use efficiency. The check Cham 1 was the lowest yielding and least efficient.

Figure 4. Identification of wheat genotypes adapted to rainfed Mediterranean climates with responsiveness to supplementary irrigation. Source: Mosaad et al. (2005).



GNR=Non-Responsiveness; GNDR= Responsiveness without Drought Tolerance; GDRL= Linear Responsiveness to Drought Tolerance; GDRQ= Quadratic Response + Drought Tolerance.

Figure 5. Grain yield (kg ha^{-1}) and water use efficiency (kg ha^{-1} mm^{-1}) of 9 durum wheat experimental lines compared with cultivar Cham 1 in Mediterranean climate. Source: M. Nachit (unpublished, 2004).



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Association among Durum Wheat International Testing Sites and Trends in Yield Progress over the Last Twenty-Two Years

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Summary

This paper highlights the successes of CIMMYT's international durum wheat yield trial over the last 22 years, based both on the shuttle-breeding approach and the Center's global network of NARS cooperators for information feedback. Without this unprecedented global cooperation, none of the impacts (for example, in improving yield under favorable and marginal environments and enhancing disease resistance) would have been possible.

Introduction

Durum wheat currently represents 8-10% of the wheat grown and produced worldwide (FAOSTAT data, 2006). It is, however, concentrated in relatively small geographical areas where it often plays a major role in the food security of urban populations and in the livelihood and nutrition of urban communities. More than 80% of the spring durum cultivars released in the developing world, covering more than 50% of the area planted to this crop, are semidwarf types, either from CIMMYT crosses or from crosses involving at least one CIMMYT parent (Lantican et al., 2005).

The widespread sowing of relatively few, widely adapted cultivars across large geographical areas underscores CIMMYT's global responsibility to keep providing national agricultural research systems (NARS) with germplasm that can advantageously replace the current cultivars and provide an opportunity for viable diversification of the cultivar base in developing countries. To do that, each year CIMMYT distributes a set of durum wheat nurseries, including the International Durum Yield Nursery (IDYN), a replicated yield trial, to more than 100 collaborators worldwide. Data returned from these yield trials represent a powerful tool to study genotype by environment interactions globally, characterize and classify testing environments, and monitor yield progress over years. Trethowan et al. (2003) analyzed data from 20 years of the Elite Spring Wheat Yield Trial (ESWYT), exploring associations between international testing sites that revealed the importance of several key locations, each representative of large geographical areas with regards to how they differentiate genotype performance. Such analyses performed on data from the Semi-Arid Wheat Yield Trial (SAWYT) allowed Trethowan et al. (2001) to critically assess the global relevance and limitations of CIMMYT's main drought testing location in Mexico and enabled them to conclude that the testing site effectively predicted genotype performance in the Indian Subcontinent, but failed to do so in areas where other types of drought stress prevail. In durum wheat, Abdalla et al. (1996) used pattern analysis (De Lacy and Cooper, 1990) to classify international testing sites based on five years data of the Elite Durum Yield Trial (EDYT) and concluded that groupings were associated primarily with latitude and water supply. In this study, we used 22 years of data from the (IDYN to: (1) explore associations among international testing sites using pattern analysis, and (2) monitor global yield progress over time.

Materials and Methods

All analyses were conducted on grain yield data (adjusted means of two replicates based on an experimental design that has changed over the years) obtained from 827 environments (or location/year combinations), representing 145 locations reporting data from 1983 (14th IDYN) to 2003 (35th IDYN). Only those durum wheat genotypes from crosses made at CIMMYT and produced through at least one round of shuttle breeding in Mexico were included in the study. Only those locations that reported results as complete datasets from at least two years were considered. Associations among international testing sites over years were determined based on how sites differentiated genotypes for yield, using both classification and ordination approaches of pattern analysis (Trethowan et al., 2003). For each of the clusters resulting from pattern analysis, the site that was the "least different" from the other sites (based on the sums of the squared Euclidian distances taken from the dissimilarity matrix for each site versus all other sites in the same cluster) in the cluster was identified as a "key location" or "most representative" site. All years/nurseries included the widely adapted check Yavaros 79, as well as, with very few exceptions, the checks Mexicali 75 and, starting in 1984, Altar 84.

Global yield progress over years was explored through regression analysis using years as the dependent variable and average nursery yield or average of the five best yielding genotypes over all reporting locations as independent variables expressed either in t/ha or in relation to the yield of the check Yavaros 79.

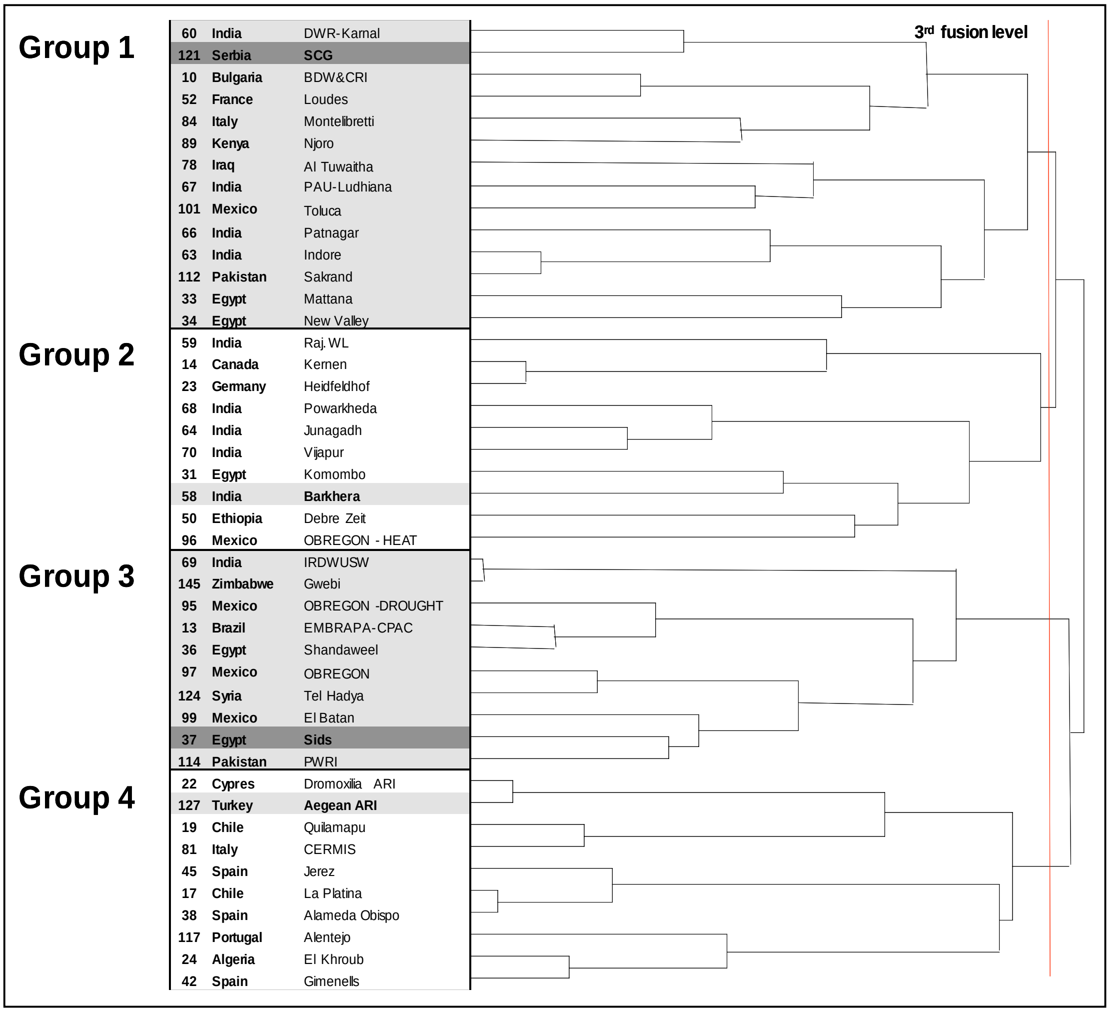
Results and Discussion

Association among international testing sites

The pattern analysis placed 44 of the 145 locations into four clusters (at the third fusion level), each including locations that differentiated genotypes similarly for yield (Figure 1). The rest of the testing sites were excluded from the dendrogram due to either insufficient data for all the necessary pair-wise comparisons to be made or to the lack of a consistent grouping trend over years, which prevented the classification of a particular site in a particular cluster. The first group included 14 sites, while the other three consisted of 10 locations each.

The first group included high yielding environments, both irrigated locations (ME1, according to the mega-environment classification used at CIMMYT) in North Africa-Middle East and South Asia (two in Egypt, one in Iraq, four in Northern India, and one in Pakistan) and high rainfall locations (ME2) in Europe (Central Italy, France, Bulgaria, and Serbia), West Africa (Kenya), and CIMMYT's Toluca station (ME2), one of the two locations used for selecting segregating material as part of the shuttle breeding program. The association between performance in Toluca and that in major irrigated and high rainfall sites worldwide contrasts with the results of Trethowan et al. (2001) and Lillemo et al. (2004) obtained for bread wheat. A poor relationship was indicated between Toluca and international testing sites with regards to performance of bread wheat from either the irrigated or high rainfall programs. This provides a preliminary suggestion that durum wheat may, to a certain extent, classify environments differently than bread wheat, and that generating data on elite durum material at the Toluca station may be justified.

Figure 1. Dendrogram from pattern analysis showing clustering of 44 international testing locations based on yield performance of CIMMYT durum wheat genotypes included in the IDYN from 1983 to 2003.



The second group represents mostly irrigated sites characterized as warm environments (ME5), including five sites in West/South India, one in southern Egypt, one in Ethiopia, and the heat testing site established by CIMMYT in Ciudad Obregon in northwestern Mexico, which uses late planting to generate heat stress through most of the plant growth cycle. However, it also includes a Canadian and a German site, both located at relatively high latitudes where photoperiod sensitivity can be an advantage. Clustering of these two sites with those characterized by high heat may be because the often late spring planting results in plants filling their grain during the hottest time of the year in those environments. Temperature data need to be compiled and related to performance in order to confirm that high temperature is the environmental basis underlying the co-clustering of these locations. If this is confirmed, it would provide support for the relevance of the late planting approach in Obregon as a method to predict performance in hot environments.

Group 3 represents primarily the high yielding irrigated sites (ME1) of northern Egypt (two sites); single sites in India, Pakistan, and Zimbabwe; ICARDA's rainfed site in Tel Hadya, Syria; and CIMMYT's irrigated station at Obregon, the other location involved in the shuttle breeding program. The co-clustering to the rainfed location of Tel Hadya and the irrigated Obregon site may appear counterintuitive, but it confirms the results of Abdalla et al. (1996) in durum wheat and those reported by Trethowan et al. (2003) for bread wheat. Interestingly, the simulated drought environment in Obregon (through withholding of irrigation) co-clustered with the full irrigation environment at the same site, indicating that performance under favorable moisture conditions is a good indicator of performance under water-limited conditions, at least under the soil and climate conditions of Obregon.

The last group included all rainfed sites with often highly variable rainfall, mostly in the northern Mediterranean coast (Spain, Portugal, Central Italy, Southern Turkey, and Cyprus), Algeria, and two Chilean sites. This is the only group that did not include a Mexican site for selection or evaluation by CIMMYT, and therefore data generated in Mexico may not be sufficiently relevant for predicting performance at those sites. Since it also includes major durum growing countries, when selecting parents for crossing particular attention should be given to performance at these locations, especially at the group's key location, the Aegean Agricultural Research Institute in Turkey.

The biplot generated with the principal coordinate (ordination) analysis (Figure 2) supports the overall grouping obtained from the pattern analysis, except that possible overlaps between groups were suggested. For example, both full irrigation and drought environments at the Obregon site, classified in Group 3 in the pattern analysis, were at the limit of quadrants corresponding to Group 1 and Group 3, and could be assigned to either group based on the biplot. This alternative classification makes sense given the similarity between the environmental and production systems of the Obregon irrigated site and the irrigated sites of Group 1. Similarly, the Egyptian, Ethiopian, and the two Indian locations clustering in Group 2 could very well be included in the quadrant corresponding to sites clustering to Group 1. A more in-depth analysis for each individual year and a study of how environmental variables may affect yield at certain locations is needed to more objectively interpret and finalize the classification of durum wheat testing environments.

Trends in global yield progress over years

Yield progress can best be assessed when genotype performance is related to a common check present at all locations and years. As shown in Table 1, the use of Yavaros 79 as a reference for estimating yield progress is highly warranted because of (1) the plasticity of its performance and its responsiveness to increasingly favorable conditions (yield ranging from 0.4 to 13.4 t/ha); (2) its overall superiority relative to other widely adapted checks such as Mexicali 75 and Altar 84, as indicated by its overall average yield and the frequency at which it figured among the five best yielding genotypes within a particular nursery; and (3) its better overall stability as determined by regression or the Wricke ecovalence parameters. This is also supported by its well-documented wide adaptation and its status as the most widely grown durum wheat cultivar in developing countries to date.

Regression analysis indicated that from 1983 to 2003 the yield trial means (in t/ha) averaged across all reporting locations (23-45, depending on the year) increased by 1.15% per year. More impressive, the means of the five best yielding genotypes (in t/ha) at each site increased by 3.75% per year. When expressed in percent of Yavaros yield, the five best yielding genotypes at each site increased by 1.43% per year.

To explore trends in yield progress in environments characterized by different yield potentials, we subdivided the environments (regardless of geographical location) into three classes based on their average nursery yield in a given year: unfavorable environments (<2.5 t/ha), intermediate environments (2.5 to 5.0 t/ha), and favorable environments (>5.0 t/ha). Based on the means of the five best yielding genotypes at each site in the same class, expressed in percentage of Yavaros 79 yield, averaged over all reporting sites in the same class, yield increases were observed of 2.08%, 1.36%, and 1.39% per year in unfavorable, intermediate, and favorable environments, respectively. In the locations corresponding to the Central, West Asia and North Africa (CWANA) region, where durum wheat is most important and Yavaros 79 sister lines play a dominating role, yield progress expressed as above was 1.2% per year when all yield levels were considered.

Figure 2. Biplot from principal coordinate analysis showing clustering of 44 international testing locations based on yield performance of CIMMYT durum wheat genotypes included in the IDYN from 1983 to 2003.

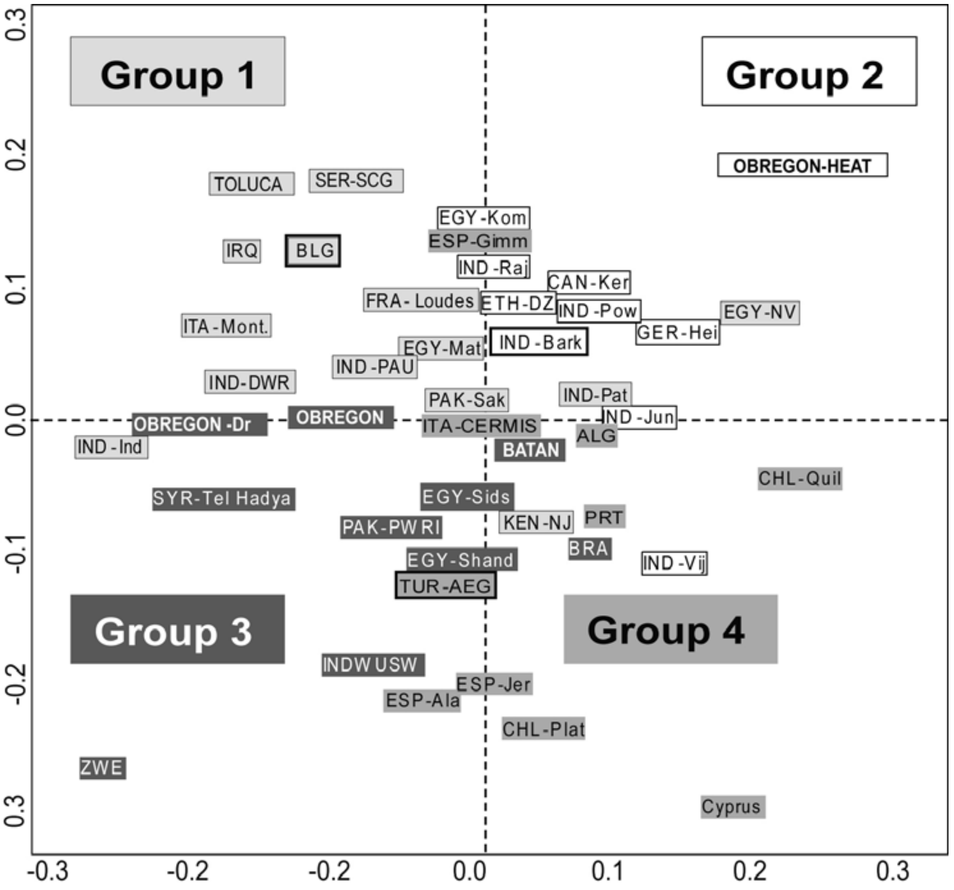


Table 1. Global performance and yield stability parameters of three checks included in CIMMYT's IDYN from 1983 to 2003.

Parameter	Mexicali 75	Yavaros 79	Altar 84
Environments tested	776	**817**	737
Yield range (t/ha)	0.3 – 12.1	**0.4 – 13.4**	0.2 – 13.0
Overall mean yield (t/ha)	4.41 ^{a*}	**4.80** ^{b}	4.78 ^{b}
% environments where Yield $_{check}$> Yield $_{mean\ top\ 5}$	8	**22**	16
Stability parameter – Regression slope	0.97	**1.02**	1.01
Stability parameter – Deviation from regression	0.064	**0.021**	0.076
Stability parameter – Wricke Ecovalence	10.51	**8.60**	11.53

* Means followed by the same letter are not significantly different at the 0.05 level.

Although these annual yield progress values (1-2%) are common in many national and local breeding programs with a local or regional focus, they can be considered remarkable when obtained by a breeding effort centralized in a single country. As for bread wheat, the international durum wheat yield trial results indicate that the concept of a centralized breeding effort in Mexico based on the shuttle breeding approach and relying on a global network of NARS cooperators for information feedback, has been successful overall. Not only did it initially provide NARS with widely adapted, high yielding semidwarf cultivars to replace landraces in most durum growing countries in the developing world, but it also maintained a steady flow of new genotypes for NARs to select from, resulting in improved yield potential over years (under experiment station conditions).

However, it should be mentioned that this overall positive assessment is based on general trends calculated by averaging results of many, often very different, locations.

Analyses for some individual locations reveal that yield progress over years was not as positive as shown by across-location analyses and was sometimes negative. Again, this calls for a detailed study of environmental conditions and disease pressure at those sites (ongoing) to understand why they failed to show yield progress over time and to then take the appropriate corrective steps. Furthermore, evidence of yield progress from test locations does not necessarily mean that the lines are being adopted by farmers, since this involves many factors other than yield potential.

Interestingly, yield progress was more pronounced in low yielding environments, which is where the majority of the world's resource-poor rural population lives. A preliminary exploration of the low yielding year/location combinations reveals that these are predominantly rainfed locations in years of low rainfall. However, a formal analysis of actual rainfall at these sites during the low yielding years needs to be conducted before we can reliably conclude that the most substantial annual progress rate occurred in drought-prone environments. Nevertheless, it is safe to suggest that the yield progress achieved through selection of segregating materials and evaluation of advanced lines in favorable environments (irrigated in Obregon and high rainfall in Toluca) has resulted in yield potential progress in favorable environments and in even greater yield increases in unfavorable, possibly drought-prone, environments. However, since performance in dry environments is substantially affected by constraints other than water limitation per se—such as abiotic (micro-element deficiencies or toxicities in soils) and biotic (root and crown rots and nematodes) factors affecting root development and stand establishment—relying on improvement of yield potential alone does not ensure that the germplasm supplied by CIMMYT to national programs will be completely relevant to their needs. Significant and concerted efforts, primarily through partnerships with NARs and advanced agricultural research institutions, to address these constraints through effective breeding strategies are required to enhanced yield stability and translate breeding achievements into improved performance in farmers' fields.

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Using Plant Breeding Data to Move from Genotype-by-Environment Interactions to Gene-by-Environment Interactions

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Summary

Genotype-by-environment interactions, especially of the cross-over type for quantitative traits, impede the development of cultivars in plant breeding programs. Progress has been made with self-pollinated cereals to identify and quantify these interactions, usually when the genotypes are cultivars or breeding lines. However, genes influencing traits of interest, such as grain yield or grain quality, are much longer lasting than cultivars, with molecular technologies providing the means of identifying allelic variation. Statistical software and computing power can now make predictions of effects and values of identifiable genes from large, unbalanced data sets for combinations of alleles across many loci.

*Using data from southern Australian wheat breeding programs, we have used these technologies to predict genotypic values for the glutenin and puroindoline genes that influence key grain quality traits in wheat (*Triticum aestivum *L.) and made predictions across 7 glutenin and puroindoline loci for 5,184 combinations of alleles at different flour protein levels. We suggest that the same molecular and statistical technologies that we have used for polygenic inheritance of grain quality can be used for polygenic inheritance of grain yield, but that relationship matrices will be more important to minimize bias. Large data sets, of the type generated by plant breeding programs, will be necessary, and can now be used with these technologies.*

Introduction

Genotype-by-environment interactions, especially of the crossover type for quantitative traits, impede the development of cultivars in plant breeding programs. Research over many decades by quantitative geneticists, plant breeders, and biometricians has produced tools for identifying and quantifying these interactions. On the genotype side, the aim of this research has been to assist with the development of stable, elite cultivars, while on the environmental side, the aim has been to better define target production environments. A further objective has often been to develop more efficient methods of evaluating potential cultivars in terms of the numbers and locations of testing environments, replications, and statistical analyses.

Many authors have emphasized identifying repeatable components of genotype-by-environment interactions (Cooper et al., 1996a; Basford and Cooper, 1998). Furthermore, a substantial effort has been made to classify and group environments so that genotype-by-environment interactions are minimized, and genotypic rankings are more consistent (Trethowan et al., 2001; Trethowan et al., 2003). The easiest abiotic environmental components to classify this way are those due to repeatable soil constraints, such as high levels of aluminum, high levels of boron, and zinc deficiency. For these, specific test environments, either field, glasshouse, or laboratory, have been devised, and relatively rapid progress has been made (Fisher and Scott, 1993; Paull et al., 1993; Delhaize and Ryan, 1995; Genc et al., 2002). Nevertheless, many questions still need to be answered. For example, although aluminum tolerance has been shown to be beneficial on acid soils in southern Australia (Scott et al., 2001), it is not known whether aluminum tolerance is detrimental on alkaline soils in the same region. If it is, this would produce a crossover interaction. Likewise, the optimum level of boron tolerance on soils varying widely in boron across relatively short distances is not known.

Due to the unpredictable nature of the Australian environment (Rimmington and Nicholls, 1993; Flannery, 1994), less progress has been made in Australia with constraints due to rainfall and temperature patterns than with more easily identifiable abiotic stresses. Nevertheless, progress has been made in understanding and classifying particular environments, and then weighting them in an overall analysis (Cooper et al., 1996b; Podlich et al., 1999; Chapman et al., 2000).

In addition to the difficulties of classifying environments, progress might also be impeded by the temporary nature of the cultivars and breeding lines being assessed. This is because the objective of plant breeding programs is to replace existing cultivars with new ones. Otherwise, the plant breeding program is a failure. Genes are much more permanent than genotypes, with allele frequencies changing as the plant breeding program progresses. By shifting the emphasis from genotypes to genes, predictions of longer-term value to plant breeders should be possible.

Predicting genotypic values

Obviously, the first step in moving from genotypes to genes is the identification of the genes or quantitative trait loci (QTLs) affecting the trait of interest. However, we suggest that the full utilization of this information for quantitative characters requires estimates of the effects of the genes in the target population of environments, either alone or, more often, in combination with other genes. Therefore, in the project that is the topic of this paper, we work with genes already identified and mapped in other projects. Central to our approach is the estimation of genotypic values for alleles contributing to traits of interest. We regard the genotypic value as the expected value of the phenotype in the target population of environments (Eagles et al., 2002c). This comes from

$$P = G + A + E$$

where P is the observed phenotypic value (a number), G is the effect of the gene (or genes) of interest, A is due to other genes (random polygenes), and E is the environmental deviation. Hence, the means from an infinitely large number of observations in the target population of environments in an infinitely large sample of background genotypes would give the genotypic values for the alleles of interest. With this model, the genes are included in the fixed part of a mixed model, while the background, unknown genes, are in the random part (Kennedy et al., 1992). As wheat is an inbreeding species, we are only interested in genotypic values at homozygosity, and we only analyze data where the allelic composition for the genes of interest are known for all cultivars or breeding lines. In animal breeding, A is a relationship matrix (Kennedy et al., 1992); we will consider the practical implications of constructing these matrices later in this paper.

The usual method for calculating genotypic values is to construct doubled-haploid populations, or special stocks, such as isolines. The statistical analysis of data from these populations is relatively easy; however, the construction of these populations, and their assessment, is often expensive, so that the data sets available to estimate genotypic values are usually small and from a small sample of the target population of environments. The genetic background is usually limited. As discussed in Eagles and Moody (2004), and by Crepieux et al. (2004) in a QTL mapping and detection context, an alternative is to use large data sets assembled as part of plant breeding. These have the advantage of obtaining estimates across large numbers of crosses and being relevant to the breeding populations of interest (Eagles et al., 2002b; Podlich et al., 2004). The disadvantage is that the data are unbalanced with the potential for biased estimates. Unbalanced data can be analyzed using REML (residual maximum likelihood), and biases can be minimized by including lines as a random term in the model or, even better, by using relationship matrices. We have found that these methods allow genotypic values for multiple alleles at multiple loci to be estimated in large data sets.

Bernardo (2002, p. 54) discussed the concept of effects of alleles. He noted that Sir Ronald Fisher used the term average effect of an allele to denote the average deviation from the population mean of individuals that received the allele from one parent, the other allele having come at random from the population. Hence, the average effect depends on the frequency of the allele and other alleles in the population of interest. Although this is useful for selection in populations for which the objective is to improve the mean of a population of individuals, such as a herd of cattle, we consider this to be less useful in breeding plants, for which the objective is to identify a superior genotype (or very closely related genotypes as occurs with F_4 or F_5-derived lines) and multiply this genotype to become a released cultivar. This is the situation with self-pollinated crops such as wheat and barley. New populations of such crops are generated easily and in large numbers by breeders, with segregating allele frequencies often 0.5 (a single cross), or 0.25 and 0.75 (a backcross or 3-way cross). Then, genotypic values of genes and combinations of genes are important for predicting breeding progress. These do not depend on gene frequencies. Interestingly, Fisher (1930) also considered populations in which mating (and thus gene frequencies) is under the control of the experimenter to be different from those where it is not. Researchers with self-pollinated crops, including ourselves, have used the term *effect* to denote differences between factor levels, such as different alleles of a particular gene. These are especially useful for predicting the genotypic value of a combination of genes.

So far, we have concentrated on predicting genotypic values across a single, large population of environments. However, the same methodology can be used to estimate gene-by-environment effects, and especially to detect when crossover interactions occur. Then, the equation is expanded to

$P = G + GF + A + E$

where GF denotes a gene-by-environment interaction component. In practice, these can be especially useful with repeatable components of the environment (F), which for analysis purposes can be included along with the identifiable genes in the fixed part of the mixed model. An advantage of using genes is that only a few alleles are considered at each locus, rather than the many genotypes often being considered with cultivars or breeding lines. This greatly simplifies the identification of crossover points.

Genes influencing grain quality

The major emphasis for breeding wheat and similar crops is improvement of grain yield. However, cultivar acceptance in countries like Australia depends not only on grain yield potential but also on other traits, especially grain quality for target markets. Many lines with high yield potential and acceptable disease resistance are not released because they fail to meet quality standards for classification into higher priced grades. If the combinations of genes required to meet grain quality standards can be identified, crosses can be designed to have a high probability of meeting the standards, and therefore higher selection intensities can be used for disease resistance and grain yield. We expect this to lead to faster progress for grain yield. This might be even more important when breeding for grain yield in complex, water-limited environments, such as those described by Passioura (2006).

We have made the most progress with the genes controlling high molecular weight glutenin proteins (*Glu-A1*, *Glu-B1*, and *Glu-D1*), the low molecular weight glutenin proteins (*Glu-A3*, *Glu-B3*, and *Glu-D3*), and the puroindoline proteins (*Pina-D1* and *Pinb-D1*). These influence dough strength (measured as Rmax), dough extensibility, dough development time, and flour water absorption. Although of importance in itself, the work on grain quality can also be viewed as a method for utilizing polygenic systems with multiple alleles for other traits, such as disease resistance and grain yield.

There are multiple alleles at the glutenin and puroindoline loci. The work of Payne and his colleagues was especially influential in identifying the glutenin genes (Payne, 1987), while the work of Morris and his colleagues was similarly important for the puroindoline genes (Morris, 2002). For prediction purposes, we regard the hardness locus, where the *Pina-D1* and *Pinb-D1* genes are located, as a single gene with three alleles, abbreviated as *Pin-aa* (soft), *Pin-ab* (moderately hard), and *Pin-ba* (very hard). Using estimates of main effects at each locus and significant 2-way epistatic interactions, such as between *Glu-B1* and *Glu-B3* (Eagles et al., 2002b), we can now predict 5,184 genotypes (3 x 6 x 2 x 4 x 4 x 3 x 3) across the *Glu-A1*, *Glu-B1*, *Glu-D1*, *Glu-A3*, *Glu-B3*, *Glu-D3*, and *Pin* loci (see Eagles et al., 2006, for identification of the alleles). These include most of those present in Australian breeding programs and many that have not yet been evaluated. For example, among these 5,184 predictions is one for a,i,d,b,h,b,ba, which is the abbreviation for *Glu-A1a*, *Glu-B1i*, *Glu-D1d*, *Glu-A3b*, *Glu-B3h*, *Glu-D3b*, *Pin-ba*, with a current predicted genotypic value of 408 BU for Rmax and 19.7 cm for extensibility, and one for b,e,a,b,b,b,ab, with a predicted value of 271 BU for Rmax and 21.1 cm for extensibility. These are the genotypes of the cultivars Diamondbird and Yanac, and their estimated values are 392 BU and 259 BU for Rmax, and 19.8 cm and 21.0 for extensibility. The agreement between predicted and estimated values for these two cultivars is particularly close. Our current assessment is that, after adjusting for flour protein, we can account for approximately 65% of the genotypic variance across the southern Australian breeding programs with this 7-locus system for Rmax and approximately 60% for extensibility (Eagles et al., 2006). Hence, 35% to 40% of the genotypic variance cannot be explained by the glutenin and puroindoline genes, suggesting that further gains can be made by the incorporation of other genes into the predictions. The quantitative trait locus on chromosome 2A recently identified by Kuchel et al. (2006) is a likely candidate for one of these genes.

The 5,184 predictions are incorporated into software called a “Cross Predictor,” which allows a wheat breeder to predict the quality profile from potential two-way and three-way crosses in his or her breeding program (Eagles et al., 2004b; Ye et al., 2004; Cornish et al., 2006). Using the properties of the binomial expansion, it calculates the minimum population sizes required for a 95% or 99% probability of obtaining progeny within desired quality ranges, even though there is genetic linkage involved (Ye et al., 2004). This allows the breeder to concentrate on crosses with acceptable probabilities of producing cultivars that can be accepted into high quality classifications and, as mentioned previously, increase the selection intensity for traits such as grain yield and disease resistance.

So far, in our published work, we have made predictions for southern Australia as the target environment and have not considered gene-by-environment interactions. However, if these interactions occur, the target environment may need to be subdivided.

Subdividing the target environment using flour protein

Although the original target was all wheat growing environments in Victoria, South Australia, and southern New South Wales, we have now divided the target into low protein environments suitable for wheat in the Australian Soft class and high protein environments in the Australian Hard class. All 5,184 genotypes are still predicted, and all the data available are used to make the predictions, with the calculations made using the VPREDICT directive in GENSTAT (Payne et al., 2003). Spline functions are used to allow for a non-linear relationship between the gene effects and flour or grain protein. Currently, predictions are made at 8.5% flour protein for Australian Soft and 11.0% flour protein for Australian Hard.

As an example of the types of predictions obtained and their precision as measured by standard errors, the data for Rmax and dough extensibility used by Eagles et al. (2006) were re-analyzed. Briefly, there were 894 lines classified for glutenin and puroindoline genes that were homozygous and not mixed, from 467 environments (site-year combinations) in southern Australia, with a total of 6,258 observations for both Rmax and extensibility. The same statistical methods based on the REML directive in GENSTAT (Payne et al., 2003) were used, except that in the current analysis, environmental flour protein was included as a spline function and the VPREDICT directive was used to make predictions at 8.5%, 11.0%, and 12.5% flour protein for all 5,184 genotypes. Environmental flour protein was estimated as the mean flour protein in each environment. In this example, epistatic interactions were not included.

Predicted genotypic values for a,i,d,b,h,b,ba, which we previously mentioned, is the genotype of Diamondbird; for a,i,d,b,h,b,ab, which is the genotype of EGA Wedgetail; for a,u,a,b,b,b,ab, which is the genotype of Janz; and for b,e,a,b,b,b,ab, which is the genotype of Yanac, are presented in Table 1. The same combinations of glutenin and puroindoline alleles are found in many relatives of these cultivars.

Table 1. Predictions of means for Rmax and dough extensibility for four genotypes of wheat at three flour protein levels.

Flour protein (%)	*Genotype*[1]	*Rmax (BU)*	*Extensibility (cm)*
8.5	a,i,d,b,h,b,ba	366 ± 10	17.5 ± 0.3
	a,i,d,b,h,b,ab	355 ± 11	17.7 ± 0.2
	a,u,a,b,b,b,ab	272 ± 9	17.2 ± 0.2
	b,e,a,b,b,b,ab	251 ±13	17.9 ± 0.3
11.0	a,i,d,b,h,b,ba	408 ± 9	20.2 ± 0.2
	a,i,d,b,h,b,ab	400 ± 9	20.8 ± 0.2
	a,u,a,b,b,b,ab	321 ± 8	20.9 ± 0.2
	b,e,a,b,b,b,ab	272 ± 11	21.5 ± 0.3
12.5	a,i,d,b,h,b,ba	416 ± 10	21.5 ± 0.2
	a,i,d,b,h,b,ab	411 ± 10	22.3 ± 0.2
	a,u,a,b,b,b,ab	333 ± 9	22.8 ± 0.2
	b,e,a,b,b,b,ab	268 ± 12	23.4 ± 0.3

[1] Genes in the order *Glu-A1*, *Glu-B1*, *Glu-D1*, *Glu-A3*, *Glu-B3*, *Glu-D3*, *Pin.*

The standard errors for these predictions are all small (Table 1). Hence, for frequent alleles in this large data set the standard errors are small. However, when the objective is to predict future outcomes, such as from a cross of Diamondbird and Janz, these standard errors are probably less important than whether hitherto unidentified genes are segregating. Therefore, we regard the identification and inclusion of further genes as important for improving the accuracy of our predictions.

The genotype a,i,d,b,h,b,ab had a significantly higher predicted extensibility than a,u,a,b,b,b,ab at 8.5% flour protein, a similar predicted extensibility at 11.0% flour protein, but a significantly lower predicted extensibility at 12.5% flour protein (Table 1). This demonstrates the complexity of interactions possible across flour protein levels. The complexity increases when epistatic interactions are included in making the predictions. The best way to handle such complexity is, we believe, by making predictions from very large data-sets that contain as many combinations of alleles as possible. In practice, especially due to cost considerations, these are only possible from plant breeding programs.

The predictions for the a,u,a,b,b,b,ab genotype at 12.5% flour protein could explain the acceptance of Janz and its relatives into the Prime Hard Classification in northern New South Wales and Queensland. This classification requires high flour (or grain) protein and high dough extensibility. High dough extensibility was predicted for the a,u,a,b,b,b,ab genotype at high flour protein levels (Table 1).

Relationship matrices and the reduction of bias

As mentioned previously, Kennedy et al. (1992) showed that biases in the estimation of the effects of genes in unbalanced data sets are minimized using mixed models, with the gene of interest included as fixed and the remaining polygenic effects included as random in a relationship matrix.

The calculation of coefficients of parentage, upon which relationship matrices are based, requires accurate pedigrees. The International Crop Information System (ICIS, see http://www.icis.cgiar.org and McLaren et al., 2005) has facilitated the assembly of these pedigrees and the subsequent calculation of coefficients of parentage; nevertheless, their assembly is a major undertaking for the hundreds to thousands of lines required to identify gene effects across multiple environments. We have found that more general relational databases, such as Microsoft Access, greatly assist with the assembly of these matrices and their export for statistical analysis by GENSTAT. However, once assembled, relationship matrices have multiple uses. For example, they can be used to predict breeding values (Panter and Allen, 1995; Bernardo, 2002), and especially breeding values corrected for known major genes, such as those providing resistance to rusts, and to therefore enhance the identification of desirable parents for the next cycle of crossing. We are using them for that purpose.

Because not all the pedigrees were available at that time, relationship matrices have not been used for the calculation of allelic effects of the glutenin and puroindoline genes. However, all genes are included in all calculations, and the lines themselves are included as a random effect. Furthermore, the lines come from a wide range of crosses (Eagles et al., 2002a) spanning decades, and the genes account for a relatively high proportion of the genetic variance, so biases are probably small. Furthermore, we have found consistency between estimates made from wheat breeding data and those from designed experiments (Eagles et al., 2002b; Eagles, unpublished). Nevertheless, a current aspect of our work is to assemble the relationship matrices for their inclusion in the estimation of genotypic values for genes influencing wheat quality.

For grain yield, we are using relationship matrices to calculate gene effects. For example, a relationship matrix was used to calculate the effect of the *Ha2* gene in barley on grain yield (Eagles and Moody, 2004; Eagles et al., 2004b). To date, these have been based on Malécot's coefficient of parentage (Malécot, 1948). Crepieux et al. (2004) have proposed using relationship matrices with plant breeding data to locate and map QTLs for traits of importance. They further suggested using molecular marker information for the development of relationship matrices. We agree that using molecular marker information in the development of relationship matrices has merit, but not at the expense of a major reduction in population size when the objective is to estimate effects and predict genotypic values. Errors in pedigrees are of concern, but characterization of lineages for major genes, especially genes that can be unequivocally characterized, can be used to detect many of these errors.

Genes affecting grain yield

Using breeding data from Victoria, the semidwarf allele of the *sdw1* gene in barley was found to increase grain yield in high yielding environments but decrease yield in low yielding environments (Eagles and Moody, 2004). The crossover point was estimated at approximately 2.0 t/ha. A relationship matrix was not used for those original calculations, but similar results were obtained with the inclusion of a relationship matrix (Eagles and Moody, unpublished). It was possible to classify semidwarf and tall alleles of this gene phenotypically, in a manner not dissimilar to that used by Mendel with dwarf and tall peas (Bateson, 1909). We are confident that there was only one semidwarf allele, as the allele can be traced to Diamant in the pedigrees, but we do not know how many alleles are being classified as tall. Molecular methods might identify several alleles being classified as tall, as has occurred for alleles of the puroindoline genes that produce hard grain (Morris et al., 2001; Cane et al., 2004), but with different properties (Martin et al., 2001; Cane et al., 2004), or with the 7 + 8 bands at the *Glu-B1* locus (Eagles et al., 2004a; Vawser and Cornish, 2004).

In addition to the *sdw1* gene, mapping population studies have identified two other genes, *eps2* and *Ppd-H1*, that affect grain weight in barley in southern Australia (Coventry et al., 2003). As grain weight, along with grain number per unit area, is one of the determinants of grain yield, these genes are also likely to affect grain yield. With appropriate molecular methods of identifying alleles of these genes, their effects could be determined by typing lines in breeding programs, assembling coefficient of parentage matrices, and using grain yield data gathered by routine operations of the breeding program in a mixed model analysis. As suggested earlier, the effects are likely to be assessed across a much greater number of other genes and in many more environments than with planned experiments.

As in barley, genes affecting height and phenology have been identified in wheat. These include the *Ppd* series of genes influencing photoperiod response, the *Vrn* genes and the *Rht* genes (Snape et al., 2001; Worland et al., 2001; Ellis et al., 2004; Borojevic and Borojevic, 2005). *Ppd-1* has already been shown to produce a crossover type interaction for grain yield of wheat in Europe (Snape et al., 2001). Genes influencing other physiological traits and likely to influence yield are also being identified (Reynolds et al., 2005). For example, progress is being made toward identifying the genetic basis for carbon isotope discrimination, a physiological trait associated with grain yield in water-limited environments (Rebetzke et al., 2006). With a molecular means of identifying alleles of these genes, their effects on yield in different environments could be estimated, desirable combinations for particular environments identified, and predictions of outcomes for particular crosses made using software similar to that in the Cross Predictor. Eventually, predictions could be made for particular environment types based on soil, rainfall, and temperature characteristics, enhancing the rate of progress possible in cereal breeding.

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Exploitation of Genetic Resources through Wide Crosses

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Introduction (diversity of wild relatives and alien species of wheat)

Bread wheat has unique evolutional history among other major cereals. It has three kinds of genomes from three different diploid ancestral species of A, B, and D genomes. The ancestral species of A genome, which is thought to be Triticum urartu Tumanian ex Gandilyan (AA) (Dvorak et al. 1993), and B genome ancestor, which is thought to be closely related to Aegilops speltoides Tausch (SS)(Terachi et al. 1988), hybridized naturally forming tetraploid species of Triticum turgidum L.(AABB) and then tetraploid wheat hybridized again with D genomes ancestor of Aegilops tauschii Coss. (Kihara 1944) forming hexaploid wheat of Triticum aestivum L. (AABBDD). According to molecular and archeological data, the formation of tetraploid is estimated in 100,000-500,000 year ago (Huang et al. 2002) and that of hexaploid is about 10,000 years ago (Hancock 1992). This evolution is well-known among wheat scientist, but it is not so well-known about bottleneck effect on diversity during specification in which only limited population of these ancestral species evolved into hexaploid wheat. Dvorak et al. (1998) reported that genetic diversity of D genome in hexaploid wheat is quite narrow comparing to the diversity of diploid D genome species of Ae. tauschii in a phylogenic tree. Ozkan et al. (2005) also reported that durum wheat originated from one part of the diversity of wild species of T. dicoccoides. Because of its huge diversity, we can expect more number of useful genes in these ancestral species than those in wheat genetic gene pool. In fact, the number of genes has been found and transferred into wheat breeding program from most kinds of wild relatives such as Ae. tauschii, T. monococcum, and Ae. tauschii as well as T. dicoccoides, T. timopheevi, and so on (For review see McIntosh et al. 2003; Tyrka and Chełkowski 2004). Besides the ancestral species, alien species of wheat can also contain much diverse genetic resource for the breeding. The genus Triticum L. belongs to the tribe Triticeae which consists of more than 300 species (Dewey 1984). Even though there are some species which seem to be extremely difficult to be hybridized with wheat, the number of reports is indicating that most of Triticeae species would be hybridized with wheat by normal crossing followed by embryo rescue (Mujeeb-Kazi 1995); therefore, most of Triticeae species can be regarded as potential genetic sources for wheat improvement. Another important thing about these alien species is that there are sources of super resistance/tolerance such as Fusarim head blight whose tolerance is close to immunity (Ban 1997) and salinity whose tolerance is high enough to be able to survive even under salt concentration of sea water (McGuire and Dvorak 1981). The wide cross group in CIMMYT has been working to capture these diverse genetic resources to wheat breeding. This review is aiming to summarize the wide cross activities in CIMMYT for the last twenty years to show its potential for the practical breeding.

The use of wild relatives in CIMMYT

Table 1 shows the list of wild relatives in CIMMYT gene bank. Our interest is to utilize many of these genetic resources for wheat breeding. Historically, however, CIMMYT has concentrated on the use of D genome ancestor of Ae. tauschii. One of reasons is that we can obtain the plants with same genomic constitution of bread wheat (AABBDD) by crossing between durum (AABB) and Ae. tauschii (DD). This artificial synthesized wheat is called synthetic wheats (SH's), and we can directly put them into breeding program. Embryo culture and chromosome doubling technique is necessary to produce SH's, but these are already established methodologies. One of interest thing is that the first synthetic wheat developed more than 50 years ago in the analysis on wheat evolution (Kihara 1944; McFadden and Sears 1946) but none was interested in using for breeding. It was prior to the Green Revolution in 1960's, maybe major impact could be achieved within the diversity of bread wheat itself between eastern and western wheats.

In CIMMYT, the production of SH's was started in 1986 by Dr. Mujeeb-Kazi about 40 years after the first production. After that time, CIMMYT has produced 50-100 new SH lines each year, accumulating about 1,100 SH of D genome (genome=AABBDD). Also, CIMMYT has also produced about 200 and 50 lines of SH's of A and B genome (AABBAA and AABBSS(~BB)) by crossing durum and A or S (~B) diploid species. Newly produced SH's have usually put on evaluation of useful traits in three different field station in Mexico, namely Obregón (dry area), Toluca

Table 1.

Species Name	Genome Constitute	Lines in CIMMYT	Lines used for synthetic wheats
Triticum turgidum L. subsp. dicoccum (Schrank ex Schübl.) Thell.	AABB	779	24
Triticum turgidum L. subsp. dicoccoides (Körn. ex Asch. & Graebn.) Thell.	AABB	880	3
Triticum monococcum L. subsp. aegilopoides (Link) Thell.	AA	880	120
Triticum urartu Tumanian ex Gandilyan	AA	392	21
Aegilops speltoides Tausch	(~BB) SS	140	34
Aegilops tauschii Coss.	DD	400~600	370-450

(temperate area and high land), and Poza Rica (tropical environment). Since the climate of the three stations is quite different each other ranging from dry area to tropical environment, it makes us possible to evaluate different abiotic and biotic stresses (Table 2). Table 3 summarizes the useful traits that we have found in the last twenty years including three kinds of rust disease, FHB, Septoria, Helminthosporium, and drought resistance. The D genome SH's are quite useful against drought stress. In 2004, about 40% of breeding material in Australia is coming from SH's related materials (Dr. Trethowan R. personal communication).

Table 2.

Field station	Latitude	Altitude	Climatic type/zone	Evaluated traits
Obregón	27.2°N	38m	Dry; Bwh	Leaf rust, Stem rust, drought
Toluca	19°N	2640m	Temperate; Cwb	Yellow rust, septoria, FHB
Poza Rica	20.5°N	100m	Tropical; Aw'	Helminthosporium

Table 3.

Traits	Number of resistance synthetic wheat of D genome (AABBDD)	Comments
Leaf rust	37 lines	
Strip rust	80 lines	
Kernel bunt	20 lines	
FHB	5 lines	Equal to Sumai#3
Septoria	20 lines	
Helminthosporium	10 lines	
Drought	35 lines	(40% breeding materials for drought tolerance in Australia)

Once we found the resistance traits, we introduce these into modern varieties of CIMMYT whose process is called pre-breeding. Since SH's have many undesirable traits of wild Ae. tauschii and its plant type is unacceptable for breeders (Fig. 1), we need to transfer only resistance traits to the varieties leaving behind undesirable traits as many as possible. In many cases, susceptible varieties are employed as current parent to confirm the transfer of the resistance factors. One crossing between SH and modern variety and the selection of progenies are often enough to have synthetic derivative lines which have good plant type of modern variety and resistance traits of SH. One more backcrossing on F1 between SH and modern variety will increase the chance to have lines of good plant type. These SH derivatives have been registered for the distribution (Table 4).

In the last 20 years, CIMMYT has utilized more than 500 accessions of Ae. tauschii as well as 200 and 50 lines Ae. speltoides and T. monococcum (Table 1). However, there are still several hundreds of accessions of diploid and more than one thousand of tetraploids in CIMMYT genebank. More efficient and rapid methodology would be preferable. Trait-Targeted production is one way to select accessions to

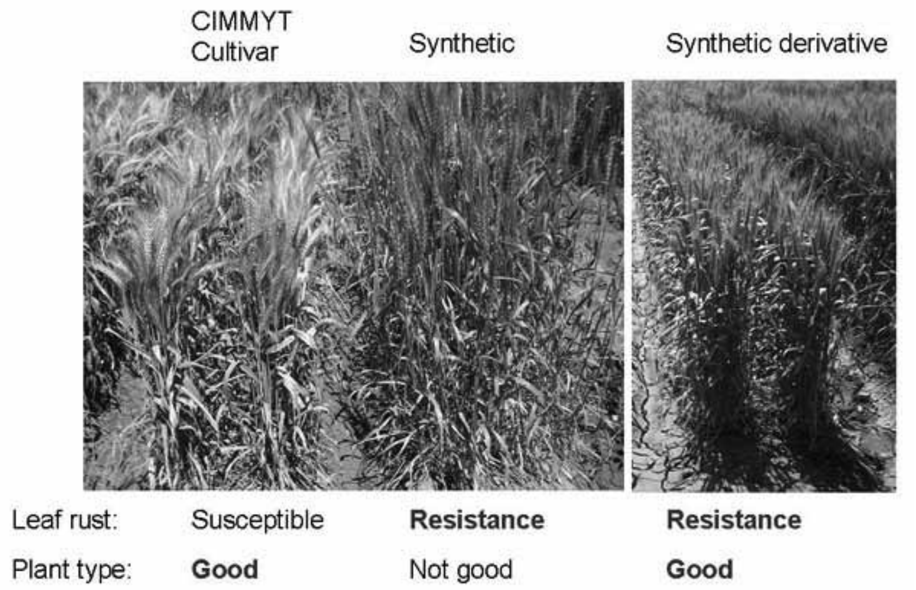

Figure 1. Prebreeding activity on synthetic wheat. The leaf rust resistance of SH is transferred to CIMMYT modern variety. The CIMMYT cultivar is susceptible in leaf rust which can be seen from the dried leaves. In contrast, SH shows leaf rust resistance, but has a poor plant type, such as non-uniform height of spikes and openness of stems, when compared to the CIMMYT cultivar. Normal breeding practice (cross of the synthetic and modern variety, followed by selection of progenies) allows us to obtain synthetic derivative lines that have both resistance and good plant type.

Table 4.

Pedigree	Registration PI number	Tolerance/ resistance trait	Reference
Croc_1/Ae. tauschii (205)//Kauz	PI 610750	Septoria	Crop Sci 40(2):590 (2000)
Croc_1/Ae. tauschii (205)//Borlaug M95	PI 610751	Septoria	Crop Sci 40(2):590 (2000)
Croc_1/Ae. tauschii (205)//Borlaug M95	PI 610752	Septoria	Crop Sci 40(2):590 (2000)
Seri M82//Croc_1/Ae. tauschii (224)	PI 610753	Septoria	Crop Sci 40(2):590 (2000)
Croc_1/Ae. tauschii (213)//Papago M86	PI 610754	Septoria	Crop Sci 40(2):590 (2000)
Altar 84/Ae. tauschii (191)//Opata M85	PI 610755	Septoria	Crop Sci 40(2):590 (2000)
Yaco*2//Croc_1/Ae. tauschii (205)/3/Yaco	PI 610756	Septoria	Crop Sci 40(2):590 (2000)
Altar 84/Ae. tauschii (224)//2*Yaco	PI 610757	Septoria	Crop Sci 40(2):590 (2000)
Papago M86/Croc_1/Ae. tauschii (224)/3/2*Borlaug M95	PI 610758	Septoria	Crop Sci 40(2):590 (2000)
Altar 84/Ae. tauschii (191)//Yaco/3/Bagula	PI 610759	Septoria	Crop Sci 40(2):590 (2000)
Croc 1/Ae. tauschii (205)//Flycatcher	PI 613312	Karnal Bunt	Crop Sci. 41:1652–1653 (2001)
Croc 1/Ae. tauschii (224)//Kauz	PI 613313	Karnal Bunt	Crop Sci. 41:1652–1653 (2001)
Altar 84/Ae. tauschii (221)//Yaco	PI 613314	Karnal Bunt	Crop Sci. 41:1652–1653 (2001)
Croc 1/Ae. tauschii (205)//Kauz	PI 613315	Karnal Bunt	Crop Sci. 41:1652–1653 (2001)
Croc 1/Ae. tauschii (205)//Borlaug 95	PI 613316	Karnal Bunt	Crop Sci. 41:1652–1653 (2001)
Croc 1/Ae. tauschii (213)//Papago M86	PI 613317	Karnal Bunt	Crop Sci. 41:1652–1653 (2001)
Altar/Ae. tauschii (224)//2*Yaco	PI 613323	Helminthosporium	Crop Sci. 41:1653–1654 (2001)
Sabuf//Altar/Ae. tauschii (224)/3/Yaco/Croc1/Ae. tauschii (205)	PI 613324	Helminthosporium	Crop Sci. 41:1653–1654 (2001)
Bcn//Sora/Ae. tauschii (323)	PI 613325	Helminthosporium	Crop Sci. 41:1653–1654 (2001)
Opata/3/Sora//Ae. tauschii (323)	PI 613326	Helminthosporium	Crop Sci. 41:1653–1654 (2001)
Bcn/4/68.111/Rgb-u//Ward/3/Ae. tauschii (325)	PI 613327	Helminthosporium	Crop Sci. 41:1653–1654 (2001)
Bcn//Doy/Ae. tauschii (447)	PI 613328	Helminthosporium	Crop Sci. 41:1653–1654 (2001)
Bcn/4/Rabi//GS/Cra/3/Ae. tauschii (895)	PI 613329	Helminthosporium	Crop Sci. 41:1653–1654 (2001)

be utilized. Several reports of target use of Ae. tauschii have been already published focusing on disease resistance (Gill and Raupp 1987; Cox et al. 1994), even though it can not capture the total diversity of species in this way. The easiest way to cover the entire diversity is to select accessions to represent entire geographical regions. Recent advance of GIS system allow us to select them with more specific data set such as precipitations, humidity, soil condition, and so on. The DNA tools are also very useful to see diversity in more detail and more precisely. It is specially the case when there is no information about the accessions and chance of mishandling of accessions which we sometimes encounter.

The use of alien species

Even though alien species is more diverse and possessing much superior resistance, it takes much more time for utilization, requiring additional cytological techniques. One big problem is the absence of homoeologous recombination with wheat chromosomes in natural condition, meaning that we can not eliminate number of undesirable wild traits in alien genome by conventional breeding methodology. Usually we need to produce translocation lines in which only part of alien chromosomes segment are translocated into wheat chromosomes, after the production of wheat-alien F1 hybrids/amphiploids, to eliminate and minimize undesirable traits. Despite of the difficulties, one good translocation has huge impact on wheat breeding. The translocation of rye chromatin, T1BL.1RS, is good example. It was useful because of its multiple disease resistance including three kinds of rust (leaf rust, stem rust, and yellow rust) and powdery mildew (McIntosh 1983) and was so effective that about 50% of CIMMYT varieties had this translocation. Increment of yield also reported at certain background (Carver and Rayburn 1994; Villareal et al. 1998). It has problem on bread making, however, showing that the size of alien fragment needs to be as small as possible. The transfer of useful traits from alien species to wheat has been also reported for improving of disease (For review see Friebe et al. 1995) as well as yield (Singh et al. 1998).

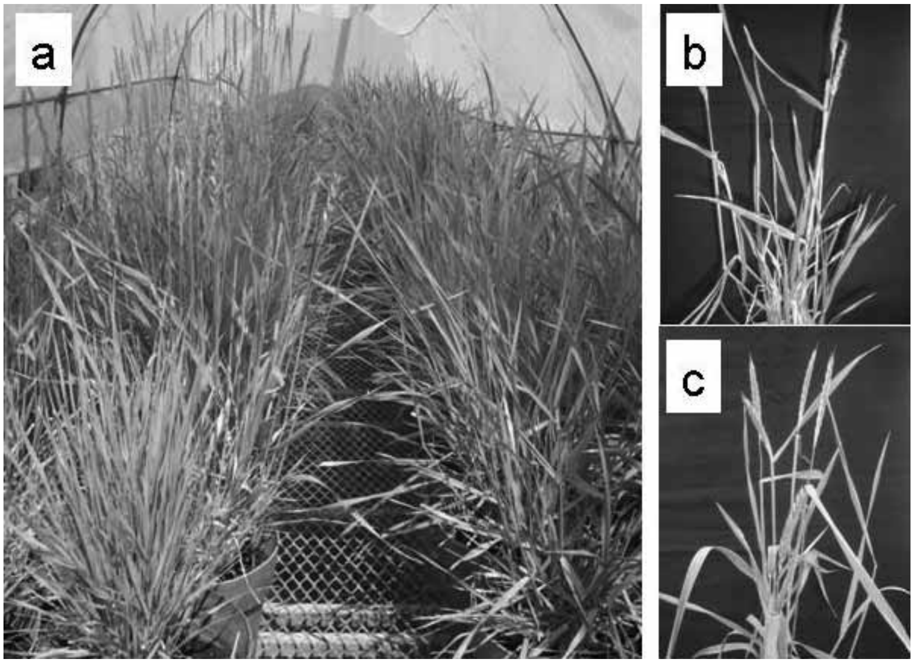

Figure 2. Plant types of F_1 and amphiploid between wheat and alien species: (a) Maintenance of various perennial F_1 plants. (b) Amphiploid between durum (BIA) and *Aegilops variabilis*. (c) Amphiploid between durum (CAPELLI) and *Ae. triuncialis*.

The last 20 years, CIMMYT has produced more than 150 F1 hybrids and 50 amphiploids between alien and wheat. Most of alien sources were coming from genus Aegilops and Thinopyrum. The plant types of all amphiploids are quite different from that of wheat cultivars and not acceptable for cultivation. We have maintained those lines, but some of amphiploids are unstable in their chromosomal number, especially in the case when total chromosome number in one plant exceeds 56 and carefully cytological checking is necessary in every seed increase. Some of amphiploids have been backcrossed with wheat to reduce chromosome number and maintained as partial amphiploids in which chromosome numbers are less than 56 (42 bread wheat chromosome + 14 alien chromosome or 28 durum wheat chromosomes + 14 alien chromosomes) and as disomic addition lines in which only one pair of alien chromosomes added to wheat. These lines, especially disomic addition lines, are usually more stable than amphiploids and easier to use. All of amphiploids, partial amphiploids, and addition lines can be employed for characterization of abiotic and biotic stresses.

Once we find good resistance sources in any of above lines, we move to produce translocation lines. Our strategy of alien translocation is to focus on traits that we can not find good sources in wheat/relatives to produce impact on the breeding, because we need to spend long time for the production. The available translocation in the world is summarized (Friebe et al. 1995). This information is quite valuable to avoid duplication of work. We have focused on FHB disease which has been serious problem in recent years in the world and we can find only limited resistance sources among wheat/relatives. We have already found several amphiploids which showed resistance equal or better than Sumai#3 (Mujeeb et al. 1984; unpublished data). Among them, we focused on Th. bessarabicum and Leymus racemosus because of availability of addition lines which we can use to identify chromosomal location of tolerance genes. There is several methodologies available for inducing translocation such as induction of homoeologous recombination between wheat and alien chromosomes by using mutants or alien gene sources of ph1b (Sears 1977) and PhI (Chen et al. 1994), induction of centromeric translocation (Sears 1952), use of radiation, gametocidal system (Endo 1988), and tissue culture. Among them, homoeologous recombination has been contributing to produce most number of translocations that have utilized in wheat breeding programs. For Th. bessarabicum, we use ph1c mutant to induce homoeologous translocation and have already obtained several translocated chromosomes (Fig. 3). Same attempt had been done on L. racemosus, although we could not have been successful without obtaining any of translocation. It may be coming from far evolutional distance between wheat and L. racemosus. For alternative, induction of centromeric translocation and other methodologies has been underway in this species.

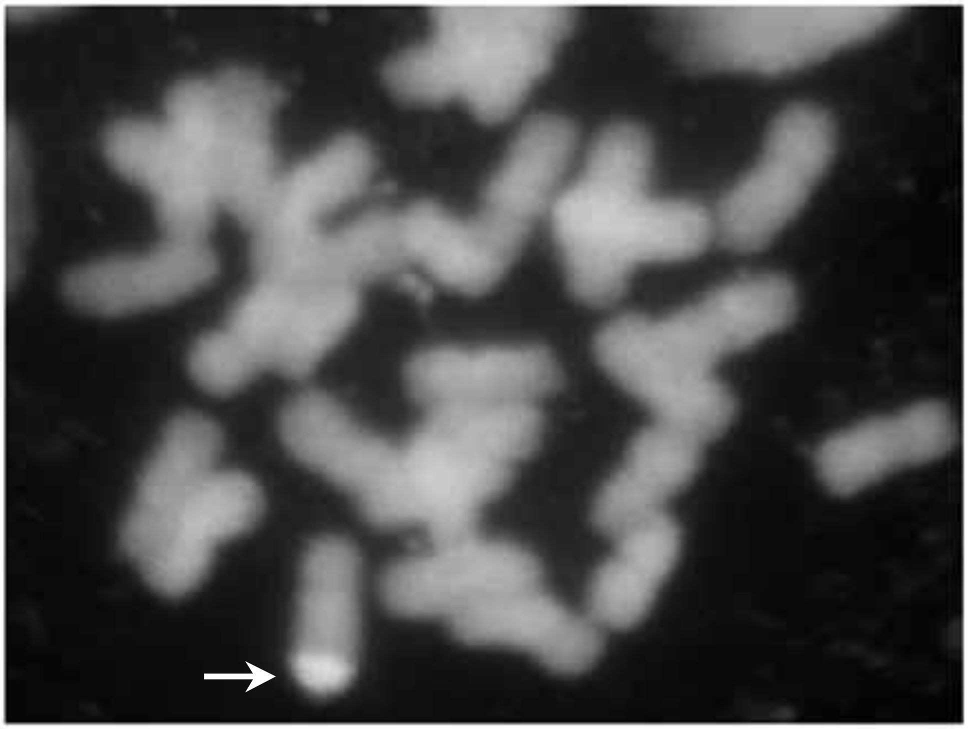

Figure 3. The *Thinopyrum bessarabicum* translocation line of wheat. Arrow indicates yellow *Th. bessarabicum* chromosome fragment translocated into reddish wheat chromatin.

Conclusion

CIMMYT is trying to capture genetic diversity of wild species as many as possible including both of ancestral species of wheat and alien species. CIMMYT has focused on the use of D genome ancestor in the form of synthetic wheats and it has been very successful, providing many useful traits against abiotic and biotic stresses for breeding program. More efficient methodology including DNA tools would be favorable to capture additional sources not only in Ae. tauschii but also in other species. Since some of alien species have superior resistance, CIMMYT is also working on this subject in long term effort.

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Stomatal Aperture Related Traits and Yield Potential in Bread Wheat

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Summary

This paper summarizes the results of a project aimed to evaluate the use of physiological traits related to stomatal aperture (such as canopy temperature, leaf conductance, and carbon isotope discrimination) in early generations of the CIMMYT wheat breeding program, to break the barriers to bread wheat yield potential. The results indicate considerable potential in the use of those tools to complement breeders' visual selection for high yield potential lines.

Introduction

It is forecast that by 2020 the world will need to produce 760 million tons of wheat per year (Rosegrant et al., 2001). This is 27% more than world production in 1997 and indicates that demand for wheat will grow by 1.3% per year worldwide and by more than 1.5% per year in developing countries. Despite this continuing increase in demand, it is expected that the area sown to wheat will change very little and that inputs to maintain high yields, such as irrigation, will actually decline significantly. This scenario indicates an urgent need for accelerating the breeding and release of wheats with increasingly higher yield potential.

Breeding wheats with high yield potential has been a major focus at CIMMYT over several decades (Reynolds and Borlaug, 2006). Published studies of wheat yield potential progress at CIMMYT indicate a steady increase (a little less than 1% per year) from the early 1960s (when GA-insensitive semidwarfing genes were first cemented in CIMMYT wheats) to the late 1980s (Sayre et al., 1997) and extending to the mid-1990s (Reynolds et al., 1999). This steady rate of yield potential gain within the CIMMYT program appears to have been maintained to the present day. For example, data presented at this symposium (Singh, on CD, Euphytica) indicates that the highest yielding advanced lines currently being tested in the CIMMYT program out-yield their recurrent parent by 15%. As it happens, the recurrent parent of these newest, high yield potential lines is Baviacora 92, which was released 15 years ago. Simple arithmetic dictates that this equals a yield potential gain of 1% per year.

The yield gains of up to 1% per year achieved at CIMMYT have been obtained by strategic choice of parents contributing exploitable diversity for improved yield and disease tolerance, followed by visual selection in early generations and empirical selection based on yield trial data in later generations. These tools have served CIMMYT well to continuously raise yield potential (Rajaram and van Ginkel, 1996), but they may be insufficient to enable an acceleration in the rate of yield potential gain to 1.5% per year, or higher. Are there additional tools that could help wheat breeders achieve the boost to yield potential gain that seems to be required if future demand for wheat is to be met? This paper summarizes results of a project aimed specifically at evaluating the use of some of these possible tools – physiological traits related to stomatal aperture – in early generations of the CIMMYT wheat breeding program.

Why stomatal aperture related traits?

Research during the 1990s at CIMMYT revealed a consistent correlation between the historic increase in yield potential among CIMMYT semidwarf bread wheats and changes in stomatal aperture related traits (SATs) (Fischer et al., 1998). The studies by Fischer and colleagues were done on a relatively small number of historically important CIMMYT releases spanning nearly three decades from the early 1960s to the late 1980s. The key finding was that more recent, higher yielding releases had higher stomatal conductance than older, lower yielding releases. They also found that yield progress was reflected in changes in traits functionally related to stomatal conductance, such as canopy temperature depression (CTD) and carbon isotope discrimination (^{13}C).

Several other studies, before and since the study by Fischer et al. (1998), have also shown positive associations between grain yield and SATs: for example, yield and CTD and yield and leaf porosity, in warm, irrigated environments (Amani et al. 1996; Reynolds et al., 1994; Reynolds et al., 1998; Gutierrez-Rodriguez et al., 2000); yield and ^{13}C, in well-watered, temperate environments (e.g., Condon et al., 1987; Condon and Hall, 1997). Often these studies have involved collections of recombinant inbred lines (RILs) or large sets of advanced breeding lines.

SATS measured in this study

In the study reported in this paper we measured canopy temperature (CT) or canopy temperature depression (CTD), leaf porosity (POR), and carbon isotope discrimination (^{13}C). Apart from their reported associations with yield, other features of these SATs make them appealing as potentially useful tools to complement conventional practice in selecting for high yield potential. Measuring stomatal conductance using conventional diffusion porometers is a relatively slow procedure poorly suited to the sampling of large numbers of plants or plots, and CT/D and POR provide much faster, alternative ways of assessing variation in stomatal conductance. Both are measured using relatively cheap, hand-held instruments and they are fast: many plots can be sampled in a short time so large numbers of lines can be assessed.

Variation in CT among entries reflects variation in how effectively the canopy is being cooled by transpiration of water from the leaves. Assuming uniform evaporative demand, the rate of transpiration (and therefore CT) is largely a function of how open the stomata are, i.e., the stomatal conductance. A single measure of CT provides an estimate of the average conductance of many leaves, because the infra-red thermometer used to measure CT samples a patch of canopy comprised of many leaves. On the other hand, POR is measured on single leaves, so several leaves need to be sampled in each plot to get an average for that plot. The measurement is fast enough that six to eight leaves can be measured within a minute, whereas a single measure of CT takes about 10-15 seconds. POR is measured using a viscous flow porometer that clamps on the leaf and pushes a standard volume of air through the stomatal pores, in one side of the leaf and out the other (Rawson and Hulse, 1996). Conductance and POR are linearly related over the range of stomatal conductance typically encountered on well-watered wheat plants (i.e., summed conductance of both leaf surfaces in the range 500-1500 mmol/m^2/s) (Rebetzke et al., 2000). But POR and CT do have at least one disadvantage. Both these "instantaneous" SATs are best measured under stable, sunny weather conditions. Even in Ciudad Obregon, Mexico (a desert environment), cloud-free conditions without strong winds occur less consistently than might be expected.

The third SAT assessed in this study was carbon isotope discrimination (^{13}C), which is a more integrative measure of stomatal conductance than either CT/D or POR. It is a measure of the ratio of the two stable isotopes of carbon (^{13}C:^{12}C) laid down in plant tissue over time relative to the ratio of these two isotopes in the CO_2 on which plants feed. ^{13}C makes up about 1% of the C in atmospheric CO_2 and fractionally less than 1% of total plant C. This is because plants of C_3 species favor the fixation of ^{12}C over ^{13}C, i.e., they discriminate against ^{13}C.

There is subtle, yet highly repeatable, genotypic variation in the ^{13}C of C_3 species such as wheat (Condon et al., 1987). To a large extent, variation in ^{13}C reflects the extent of stomatal limitation on carbon uptake. More precisely, it reflects the balance between CO_2 supply to the leaf interior (as set by the stomatal conductance) and the rate of CO_2 drawdown once inside the leaf (as set by the amount and activity of photosynthetic machinery). The greater the stomatal limitation (i.e., the lower the stomatal conductance) per unit photosynthetic machinery, the smaller the discrimination against ^{13}C and the greater the ratio of ^{13}C:^{12}C measured in dry matter. Leaf or grain dry matter can be used for sampling variation in ^{13}C. This dry matter is dried and finely ground, and only a very small sample is analyzed for ^{13}C:^{12}C ratio using a specialized laboratory instrument, an isotope-ratio mass spectrometer.

Measuring ^{13}C is considerably more expensive than measuring CT or POR, but it can be done on freshly sampled dry matter or on dry matter that has been dried and stored for a long time. Sampling the dry matter can be done at any time, so it is not weather-dependent. Measuring ^{13}C also gives a much more time-integrated measure of stomatal conductance because the carbon in the sampled dry matter is laid down over a period of days to weeks.

Details of the Study

Germplasm

Large sets (n=48-62) of random, F_3-derived, recombinant inbred lines (RILs) from five crosses were sown in three consecutive years under temperate, high radiation conditions at CIMMYT's irrigated field station at Ciudad Obregon in northwestern Mexico (27 20°N, 109 54°W, 38 m ASL). Lines consisted of random F_3-derived bulks grown between F_1 and F_3 as low density bulks without selection pressure, except for some truncation to remove extremes for phenology and height. Populations studied were from two crosses already known to be varying for SATs among the progeny (Siete Cerros/Seri 82; Quarrion/3*Genaro 81), and three crosses among parents selected from CIMMYT breeders' crossing blocks on the basis of high yield potential and measurements of SATs (Ures/Jun//Kauz/3/SW89.3243; SSeri1/SW89.3243; SW89.3243//Chil/2*Star). All parents were generated by the CIMMYT program except Quarrion, which is an Australian "semi-winter" cultivar with a pedigree strongly based on CIMMYT parents. The populations were grown in three consecutive years (2001-02, 2002-03, and 2003-04), referred to henceforth as the 2002, 2003, and 2004 growth cycles, when the populations were at F_5, F_6, and F_6 (repeated), respectively.

Field trial management

The 5 populations were sown in 8 m^2 yield plots, consisting of 2 raised beds with 3 rows per bed, and in small plots of 1.6 m^2 (2 m x 2 rows on one raised bed), simulating breeders' early-generation observation plots. For both plot sizes, trials were sown with 2 repetitions using randomized lattice designs incorporating repeated checks. Plots were sown in mid to late November each year, anthesis had occurred by early March, and plots were harvested after grain maturity in late April. All plots were sown N-S. Plots received 5-6 irrigations of *ca*. 100 mm each year, the first either immediately before or immediately after sowing, depending on seasonal conditions. Weeds were controlled by early herbicide application and subsequently by hand. Pests and diseases were controlled with foliar sprays when necessary. Nitrogen (150 units/ha) and phosphorus (25 units/ha) fertilizers were applied to achieve 80-90% of maximum yield potential of 7-8 t/ha (Sayre et al., 1997), while minimizing lodging.

Measurements

Grain yield was measured by machine-harvesting yield plots. Machine-harvested yield data was also collected on the small plots. Data on SATs was collected on small plots to simulate the use of SATs in breeders' observation plots. A visual estimate of yield potential (1-10 scale) was also taken on small plots in 2003 and 2004.

Leaf porosity (POR) of six to eight flag-leaves per plot was measured using a Thermoline viscous-flow porometer. Raw data from the porometer (counts) were inverted (1/counts) to generate data linearly related to stomatal conductance over the range of counts measured on irrigated wheat plants (Rebetzke et al., 2000). Single sets of data were collected from each plot once in the 2 weeks before anthesis (boot stage) and once in the 2 weeks after anthesis (grainfilling) in 2002 and 2003. Leaf porosity data were collected 3 to 12 days after irrigation and on cloud-free days between 1000 h and 1500 h. Days of high wind were avoided.

Measurements of CT in 2003 and 2004 or, in 2002, CTD (equals air temperature minus canopy temperature, whereby cooler canopies give larger values of CTD) were taken on each small plot using a Telatemp infra-red thermometer pointed towards the north (away from the sun) and downwards at an angle towards the center of the plot. The thermometer was held at an angle to the row direction so that no soil was in the field of view of the thermometer (Reynolds et al., 1998). Measuring CT/D is faster than measuring POR, but CT measurements are more subject to short-term environmental variation due to changes in wind speed and air temperature and humidity. Repeated measures of CT were taken to overcome this problem. Data were collected at least three times per plot both before anthesis (boot stage) and again after anthesis (grainfilling). Data were collected 3-18 days after irrigation on cloud-free days between 1000 h and 1500 h. Data from days of high wind were excluded from statistical analyses due to high error variance.

Samples for carbon isotope analysis were collected in 2002 only. Recently expanded leaf material was sampled in early January, near the time of full ground cover. Subsamples of grain were taken after machine harvest. Samples were not collected from Cross 5. Leaf and grain samples were oven-dried and ground finely for isotope analysis. This analysis was done using a Europa ANCA sample preparation system connected to a 20-20 ratio mass spectrometer (PDZ Europa Ltd, Cheshire, UK). Values of ^{13}C were calculated assuming a ^{13}C of air of -8‰ (Condon et al., 1987).

Statistical analysis of data

Data were analyzed using mixed models (REML) after checking for normality and error variance homogeneity. Data transformation was not required.

Results

Variation in yield and SATs

Average yields harvested from the large yield plots were a little over 5 t ha^{-1} and ranged significantly among genotypes within populations from more than 6 t ha^{-1} to less than 3.5 t ha^{-1}. Average yields harvested from the small plots used for SAT measurements and the ranges in yield variation among lines within populations were very similar to those in the large plots, consistent with the similarity in the general growth environments at the two plot scales. SATs also varied highly significantly among lines within populations. For ^{13}C, the range of variation was on the order of 1.5 to 2.0‰. The average value for leaf ^{13}C across populations was 18.4‰, a little higher than for grain ^{13}C (17.9‰).

Values of POR also tended to be greater when measured earlier in the season, averaging about 8 POR units at boot stage and 5 POR units during grainfill. Conversely, the range of variation for POR within populations tended to be greater during grainfill (up to 5 POR units) than at the boot stage (2-3 POR units). Because of the physical parameters that determine CT/D, average values of CT/D tend to more strongly reflect ambient conditions (air temperature, humidity, and wind speed) than leaf morpho-physiological state. Nonetheless, averaged across sampling events, there was also highly significant within-population variation in CT/D, on the order of 1 to 1.5 ºC during the boot stage and 1.5 to 2 ºC during grainfill. Among the SATs, values of broad-sense heritability (h^2) were similar to those of yield. Heritability was highest for grain ^{13}C, which at 0.75 was similar to that of large-plot yield averaged over three years (h^2 of 0.72). The other SATs (leaf ^{13}C, POR, and CT/D) had values of h^2 in a single year that averaged between 0.6 (similar to the average h^2 of single-year, large-plot yield) and 0.4 (similar to the average h^2 of single-year, small-plot yield).

Genetic correlations of SATs with yield

The genetic correlations (Rg) between SATs measured on small plots and yield measured in larger yield trial plots are summarized in Table 1, where, for simplicity, data are averaged across populations and years. For the most part, average values of Rg were highly significant (0.4 or greater). When averaged across populations, values of Rg were close to 0.5 for ^{13}C, measured only in 2002, about 0.6 for POR, measured in 2002 and 2003, and about -0.65 for CT/D, measured over all three years.

The positive values of Rg for yield with ^{13}C and POR indicate that higher yield was genetically associated with more-open stomata, i.e., higher values of POR and ^{13}C. Canopies with more-open stomata should be cooler than canopies with more-closed stomata. Hence, yield and CT (measured in 2003 and 2004) showed negative genetic associations for all populations. Under high-input, irrigated conditions such as in these studies, CT is almost invariably less than air temperature. Canopy temperature depression (CTD) is therefore greater for cooler canopies, such as those with more-open stomata. Consequently, genetic associations of yield with CTD, measured in 2002 only, were positive. In Table 1 these associations have been ascribed negative values purely for convenience, to allow averaging with Rg values for CT.

Table 1. Summary of genetic correlations (Rg) between SATs measured in small plots and yield measured in large plots for each of 5 populations of RILs. Values presented were calculated by determining Rg for all available SAT/yield combinations across years, and averaging. Yield was measured over 3 years (2002, 2003, and 2004); SATs as indicated in the table.

	^{13}C		POR		CT/D[1]		Mean[2]
Cross	**Leaves**	**Grain**	**Boot**	**Grainfill**	**Boot**	**Grainfill**	
Siete Cerros/Seri 82	0.67	0.76	0.71	0.87	-0.62	-0.87	0.75
Quarrion/3*Genaro 81	0.48	0.49	0.63	0.77	-0.37	-0.49	0.54
Ures/Jun//Kauz/3/SW89.3243	0.55	0.43	0.64	0.44	-0.47	-0.67	0.54
SSeri1/SW89.3243	0.35	0.31	0.17	0.24	-0.76	-0.72	0.43
SW89.3243//Chil/2*Star	nm[3]	nm	0.60	0.79	-0.78	-0.65	(0.71)
Average Rg	0.51	0.50	0.55	0.62	-0.60	-0.68	
No. of years for SATs	1	1	2	2	3	3	
SAT/year combinations averaged	3	3	6	6	9	9	

[1] For CT/D, all values of Rg were positive for CTD measured in 2002, but these have been assigned as negative to allow averaging with negative Rg values for CT measured in 2003 and 2004.

[2] All values of Rg for CT/D are assumed positive for calculating mean values of Rg across traits. The mean Rg for SW89.3243//Chil/2*Star is shown in brackets because it does not include Rg values for ^{13}C.

[3] 'nm' indicates that leaf and grain ^{13}C were not measured for this cross.

The magnitude of genetic correlations varied with population, being on average highest for the Siete Cerros/Seri 82 cross and lowest for the SSeri1/SW89.3243 cross (Table 1). This difference largely reflected variation in how closely different SATs were associated with yield in particular crosses. All SATs showed strong associations with yield for the Siete Cerros/Seri 82 cross. Yield and CT/D were strongly associated for SSeri1/SW89.3243, whereas the associations of yield with POR and ^{13}C were considerably weaker for this cross. For the Quarrion/3*Genaro 81 cross, POR showed the strongest associations with yield. The reason for these inconsistencies among crosses and SATs is not clear. POR measurements tended to be restricted to the first half of the period between irrigations, whereas some CT/D measurements were taken later in the period between irrigations, when available soil water may have been more depleted. It may be that genetic associations of yield with ^{13}C were weaker than with CT/D and POR because variation in ^{13}C reflects not just variation in stomatal conductance but also variation in photosynthetic capacity.

Correlated response of yield to selection based on SATs

One objective of this study was to establish the extent to which genotypic differences in SATs were reflected in genetic gains in yield. This was done by calculating the correlated phenotypic response of 3-year plot yield to selection for the best 25% and worst 25% genotypes based on their average SAT values. To simplify presentation, the results are summarized over crosses and years in Table 2. Despite ^{13}C showing smaller genetic associations with yield than either CT/D or POR, this was not reflected in yield gains associated with divergent selection for SATs. Of all three SATs, the correlated phenotypic response of yield was greatest for ^{13}C, at about 40 g m^{-2}. The response was similar for ^{13}C of leaves and ^{13}C of grain. POR, measured at either boot stage or during grainfill, and CT/D, measured at the boot stage, were associated with a yield gain of a little over 30g m^{-2} on average, while CT/D measured during grainfill was associated with a 25 g m^{-2} gain from indirect selection. Interestingly, and in contrast with ^{13}C, CT/D at grainfill showed, on average, the strongest values of Rg with yield, yet it gave the smallest correlated phenotypic response of yield to divergent selection based on SATs. The yield gains from divergent selection are in the context of average trial yield levels of about 500 g m^{-2}, and therefore represent relative yield gains ranging from about 8% for ^{13}C to 5% for CT/D measured during grainfill.

In these experiments we also measured small-plot yield, which was found to be a better predictor of large-plot yield than any of the SATs. Divergent selection for small-plot yield was associated with an increase of 52 g m^{-2} in large-plot yield (Table 2). This result may reflect the similar layout of the small and large plots sown in this study. Plots at both scales were sown on narrow beds, one 2-m bed for the small plots and two adjacent 5-m beds for the large plots. Breeders' yield plots are no longer sown as solid stands at Obregon, but on two beds that give access to light, water, and nutrients from a furrow down the center of each plot. This may favor a reasonably strong association between yield measured on observation plots and yield measured in large plots.

Table 2. Phenotypic response of grain yield in large plots, averaged over 3 years for 5 populations, to positive and negative selection based on traits measured in small plots.

Trait	No. of years trait measured	Yield difference[1] (g m^{-2})
Small plot yield	3	52.0
^{13}C of grain	1	41.0
^{13}C of leaves	1	38.1
Visual selection	2	33.2
CT/D at boot stage	3	31.4
POR at boot stage	2	30.6
POR at grain-filling	2	30.5
CT/D at grain-filling	3	25.5

[1] Yield difference equals yield of 25% best-selected lines, based on traits, minus yield of 25% worst-selected lines.

The phenotypic yield response to visual selection (breeders' score on a 1-10 scale) was also determined in 2003 and 2004. In large plots yield response to divergent selection based on visual score on small plots was 33 g m^{-2}, comparable to the yield response based on CT/D measured at the boot stage and POR measured at either stage (Table 2). Since it is routine for breeders to do visual scoring of yield potential on observation plots, at least at CIMMYT, multiple regression analysis was conducted with visual scoring and CT to establish if there was any benefit from measuring CT in addition to visual scoring. (In this case, only the complementarity of CT and visual score was assessed, since visual scoring was not done in 2002, when ^{13}C and POR were measured). The results of analyses on all five crosses combined over two years indicate that while between 13 and 56% of yield could be explained using either measure, a significantly higher proportion of yield, 26 to 63%, could be explained by combining both measures (Table 3). Using visual scoring alone was most effective for the older of the five crosses, Siete Cerros/Seri 82 and Quarrion/3*Genaro 81. Visual scoring was less effective, compared with CT alone, for two of the three crosses made among elite parents chosen from the breeders' crossing block at the start of this study, Ures/Jun//Kauz/3/SW89.3243 and SW89.3243//Chil/2*Star. Visual scoring and CT were equally effective for the cross SSeri1/SW89.3243.

Discussion

Each of the SATs evaluated in this study—canopy temperature (CT/D), leaf porosity (POR), and ^{13}C—can be measured relatively easily in breeding populations. Each was shown to have relatively strong genetic associations with yield under the irrigation regimes and environmental conditions encountered at Obregon. Further, there was substantial response of yield to retrospective selection based on each of the SATs. It would only be in very unusual circumstances (e.g., catastrophic damage to yield plots prior to harvest) that SATs might be used as a substitute for yield-testing of advanced lines in replicated trials. A much more likely scenario is that SATs would be used alongside visual selection to help identify those entries to be advanced to the yield-testing stage. In this study, SATs appeared as effective as visual selection in identifying lines with higher yield potential.

Table 3. Multiple regression analysis of the association between yield measured on large plots and visual scoring (1-10 scale) and canopy temperature (CT) measured an small plots, for 5 populations, combined over 2 years.

Cross	Step[1]	Variable	Model r^2	F	P value
Siete Cerros/Seri 82	1	Visual	0.56	79.51	0.001
	2	CT - boot	0.63	10.93	0.01
Quarrion/3*Genaro 81	1	Visual	0.24	15.33	0.01
	2	CT - boot	0.32	5.74	0.05
Ures/Jun//Kauz/3/SW89.3243	1	CT - boot	0.17	10.21	0.001
	2	CT - grainfill	0.23	3.50	0.17
	3	Visual	0.26	1.72	0.20
SSeri1/SW89.3243	1	CT - boot	0.13	8.86	0.01
	2	Visual	0.26	7.02	0.01
SW89.3243//Chil/2*Star	1	CT - boot	0.17	9.68	0.01
	2	Visual	0.23	4.15	0.05

[1] For each cross, the first step in the multiple regression model is attributed to the trait explaining the highest proportion of variation in yield, as indicated by increments in the model r^2 value. F values for each model step are indicated, along with levels of statistical significance (P).

Multiple regression analysis was used to test the complementarity of visual selection and one of the SATs, canopy temperature. The analysis revealed that substantially more yield variation could be explained by the combination of both CT and visual scoring. This result needs to be explored more comprehensively, but it is supported by data from a preliminary study on CTD conducted by van Ginkel et al. (2004, and p. 134, this volume). In that study it was found that when visual selection by the breeder was complemented by CTD measurements, almost three times more high yielding lines were identified compared with visual selection alone. In addition, incorporating measurements of CTD led to the retention of considerably more lines in the highest-yield cohort. Given that selection in segregating generations must take into account multiple factors, such as disease tolerance, appropriate phenology, etc., if these physiological criteria are to be applied in breeding programs, it would be logical to apply visual selection pressure for simple traits such as agronomic type and disease tolerance in the earliest generations (say, F_2 to F_4) to eliminate obviously unsuitable lines, while selecting for more quantitative physiological criteria such as SATs in later generations, say from F_4 onwards, when lines are more genetically fixed.

An important consideration for the utility of SATs in breeding programs is the resources needed to measure SATs relative to the resources required for other activities. Brennan et al. (on CD, Euphytica) report on a detailed economic assessment of the cost effectiveness of the different SATs used in this study. In summary, the economic assessment found that the two SATs measured using hand-held instruments, CT/D and POR, both had a low cost of measurement (*c.* 0.2-0.3 US\$ plot^{-1}) compared with yield testing (*c.* 12 US\$ plot^{-1}) because of the low cost of the equipment needed for CT/D and POR and because both can be measured by relatively unskilled labor. The analysis indicates a potentially high return to investment from applying these cheaply-measured SATs. In fact, Brennan et al. (*op. cit.*) calculate that, even though no equipment is needed, the cost of visual scoring is actually a little greater than CT/D or POR, (*c.* 0.45 US\$ plot^{-1} for visual scoring) because highly-trained staff are required for this task. In contrast to CT/D and POR, the cost of a single ^{13}C analysis (*c.* 10 US\$ plot), coupled with other labor and equipment costs means that the per plot cost of measuring ^{13}C is at least as great as the cost of a yield plot, so ^{13}C is unlikely to be used in routine screening in early generations. Similarly, even though yield measured on small plots was found to be a slightly better indicator of large-plot yield than any of the SATs, the cost of small-plot yield testing would also be prohibitive.

CT/D and POR are considerably cheaper than ^{13}C or small-plot yield, but successful collection of useful data sets of both instantaneous traits is dependent on stable, sunny weather conditions. In our experience, CT/D is somewhat more susceptible than POR to fluctuations in wind speed. On days with light, fluky winds, all canopies will tend to warm quite rapidly if there is no wind, because it becomes relatively difficult for the canopies to transpire into the pool of moist air caught in the unstirred boundary layer of air around them. If the breeze picks up, however briefly, there can be large, rapid cooling of canopies as the warm layer of moist air is replaced by drier air that promotes rapid transpiration. Changes in CT/D that result from these changes in wind speed, air temperature, and humidity tend to be somewhat uncoupled from stomatal conductance, which can remain relatively constant throughout. Thus POR measurements tend to be relatively insensitive to changes in wind speed, at least until the wind becomes quite strong, for example, sufficiently strong that it becomes difficult to grab hold of the leaf to be measured. The best conditions for measuring CT/D are therefore when there is a relatively stable, relatively gentle breeze, and there are no clouds to cause rapid fluctuations in incoming solar energy. POR measurements also require that there are no fluctuations in irradiance, as stomata open and close quite rapidly in response to changes in irradiance.

When considering the genetic correlation of SATs with yield, there was a tendency for both POR and CT/D to show higher Rg when they were measured during grainfilling than when they were measured during booting, while for ^{13}C there was no difference between ^{13}C of leaf and ^{13}C of grain in Rg with yield (Table 1). However, when considering the correlated phenotypic response of yield to divergent selection based on SATs, there were no consistent differences when comparing SATs at different growth stages, except for CT/D where genetic gains were larger for CT/D measured at the boot stage than CT at grainfill. (Table 2). Overall, these results indicate that SATs measurements are relatively insensitive to stage of development, supporting the conclusion from earlier studies in a warmer environment (Amani et al., 1996).

Physiological basis for the associations of SATs and yield

The physiological traits measured here – CT/D, POR, and ^{13}C – are all related to stomatal conductance. Genetic variation among lines in stomatal conductance may reflect heritable variation in morphological characteristics such as the size and number of stomatal pores. Such morphology-driven variation in stomatal conductance may be sufficient in its own right to generate variation among lines in the rate of carbon gain that is directly reflected in crop biomass or yield. Thus, variation in stomatal conductance would be reflected as variation in radiation use efficiency (RUE), with higher conductance lines having higher RUE and perhaps higher biomass. Biomass variation was not measured on the populations of RILs grown in this study, so associations between SATs and biomass could not be tested. Fischer et al. (1998) found no association between SATs and biomass in their study of key CIMMYT semidwarf wheats released up to 1988, even though there were strong associations between grain yield and SATs. From a study of the association between ^{13}C and yield among (mainly) released cultivars, Condon et al. (1987) concluded that, while variation among entries in the rate of carbon gain was likely a contributing factor to the large genotypic variation in biomass and yield they observed, the extent of yield variation appeared too great to be explained simply by the direct effects of conductance on carbon gain.

Variation in stomatal conductance may also reflect variation in the response of lines to a number of physiological and metabolic processes. For example, high stomatal conductance may be indicative of a high demand for photo-assimilates caused by many, rapidly filling kernels (i.e., sink strength) in physiologically well adapted lines. This hypothesis is supported by the observation that SATs may show a higher association with final yield and grain number than with above ground biomass (Condon et al., 1987; Fischer et al., 1998). But the hypothesis seems to be countered by observations of yield-related differences in SATs well before anthesis in the present study and also the study by Fischer et al. (1998), i.e., genotypic variation in SATs was apparent well before large differences in sink strength might have been anticipated. There are several other hypotheses that could explain the relationship between SATs and yield; they are not mutually exclusive, in that their application may vary depending, for instance, on crop growth stage or environmental conditions: (1) high stomatal conductance may reflect an intrinsically higher metabolic capacity before anthesis that sets up a larger grain number which subsequently drives greater demand after anthesis; (2) high stomatal conductance may be indicative of a good vascular system capable of meeting evaporative demand, or (3) high stomatal conductance may reflect a less conservative response to reduced soil water potential or evaporative demand between irrigation events. Hence, there may be genetic diversity among lines for root signalling which can cause reduced stomatal conductance in response to soil water deficits which are not actually limiting potential evapotranspiration or there may be genetic diversity among lines for stomatal response to vapor pressure deficit reflecting hydraulic status of the leaves. As part of the ACIAR-funded project that supported the work reported in this paper, we investigated several of these hypotheses and could not eliminate any of them.

Conclusion

The results of this study indicate considerable potential for the use of SATs in early-generation testing to complement breeders' visual selection for lines with high yield potential. Further work is required using breeders' populations and expertise to establish an optimal integration strategy of SAT measurements into full-scale breeding operations. Use of SATs in this way should lead to more effective culling of low yield potential lines, thereby reducing the number of such lines that advance to expensive multi-environment yield testing. This should then mean that high yielding elite lines are identified more readily, at lower cost, freeing resources to allow breeders to sample more crosses and increasing the probability of generating gene combinations for even higher yield. In a companion paper, Reynolds et al. (p. 136, this volume) discuss how such gene combinations might best be generated, arguing that a promising avenue for generating higher yield lies in improving the balance between source traits and sink traits.

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Complementing the Breeder's Eye with Canopy Temperature Measurements

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Summary

This paper focuses on the use of canopy temperature depression during the selection of segregating generations to positively skew gene frequency for yield and adaptation. The study reported here made it evident that the combination of canopy temperature depression with visual selection improves the rate of genetic progress and was the approach that identified lines with the highest yield potential.

Introduction

Canopy temperature depression (CTD) has been studied widely on a range of wheat genotypes under drought stress (Blum et al., 1982; Blum, 1988) and heat stress (Reynolds et al., 1994; 1998; Amani et al., 1996), and impressive correlations with yield in breeding populations were found. Clearly crops with cooler canopies cope better under stress than those with warmer canopies, ultimately resulting in higher biomass and yield. Those plants with cooler canopies are better able to regulate stomatal conductance (Amani et al., 1996; Fischer et al., 1998) leading to cooler leaves compared to ambient conditions.

To some extent it is logical that under stressed conditions, particularly high temperatures, CTD is useful in differentiating genotypes for yield. However, under optimal conditions, without moisture or temperature stress, a cooler canopy has also been shown to be associated with yield progress in a small set of cultivars and is probably associated with improved sink strength (Fischer et al., 1998). This has led to studies to examine the association in populations of random inbred lines under the same conditions with similar results (Condon et al., p. 126, these proceedings). However, a critical question related to application in breeding is to what extent the trait can be used during the selection of segregating generations to positively skew gene frequency for yield and adaptation. The specific aims of this study were to (1) measure the value of selection using CTD in breeding wheat for high yield potential, and (2) determine the extra genetic gain, if any, from integration of CTD measurements with selection using the breeder's eye.

Materials and Methods

In this study we compared four crosses among four CIMMYT spring bread wheats, differing in yield potential, plant architecture, and CTD: Attila x Babax, Attila x Lucero, Babax x Borlaug F95, and Borlaug F95 x Lucero-M. The materials were advanced using the modified bulk breeding method, in which individual F_2 plants are selected and maintained as individual bulks from F_3 through F_6. At F_6, individual spikes are selected and sown separately and new, near homozygous advanced lines are then selected from among these head rows. CTD measurements were first recorded in the F_4 generation on two-row 1-m plots, each derived from a separate F_2 plant; at the same time, all F_4 plots were visually selected independently by the breeder. Measurements of CTD were made two and four times on sunny still days during grainfilling. Earlier and later generations were selected visually by the breeder in accordance with ongoing breeding practices. An unselected bulk of each cross was also maintained and multiplied without selection alongside the selected generations.

This approach resulted in three germplasm flows: 'Breeder', 'Breeder+CTD' and 'Bulk.' The total number of lines per germplasm flow differed at each generation, as the breeder visually selected only the best genotypes within each cross (Table 1). The materials were developed using shuttle breeding between two contrasting locations in Mexico, thereby allowing the advancement of two generations a year. The crosses were made at Ciudad Obregón in northwestern Mexico (27°N, 60 masl), and the F_2, F_4 and F_6 generations were grown at the same location. Alternating generations were planted in the Toluca Valley (19°N. 2,640 masl). The site in northwestern Mexico is an arid, irrigated location with clear sunny skies during much of the crop growth period, which is ideal for taking CTD measurements. All generations were grown on raised beds under well-watered and optimally fertilized conditions.

Yield trials of the resulting near-homozygous lines from all three germplasm flows were carried out at Ciudad Obregón on raised beds under fully irrigated and optimally fertilized conditions during three crop cycles (November-April in 1999-2000, 2000-2001, and 2003-2004). The trial design was a latinized alpha-lattice with two replications, and each trial plot consisted of two beds, 4 m in length, with three rows sown per bed. One hundred and fifty units (150) of N were applied, 75 units days before planting and the rest at first node. The seeding rate was 100 kg/ha, and the harvested area of each plot was 6.4 m^2. Yield data from each trial were analyzed using SAS PROC MIXED {#183}, with genotypes considered to be fixed effects and years, replicates and sub-blocks within replications as random effects. Adjusted means were obtained and used for all subsequent analyses.

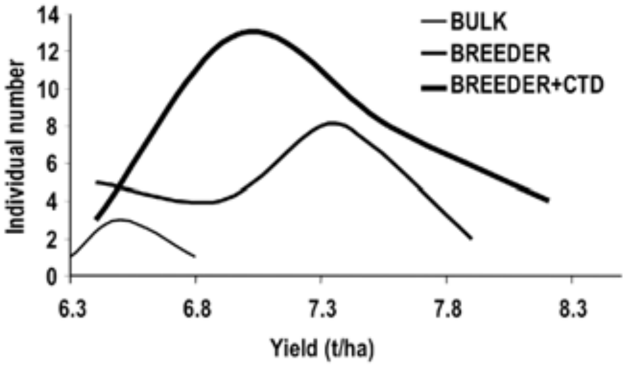
Results and Discussion

Fifty percent of the variation in yield under these *optimum* conditions was explained by cooler canopies ($r^2 = 0.55$ ($P = 0.001$)), when analyzed across all crosses and germplasm flows. Overall, 'Breeder+CTD' and 'Breeder' selection were superior to 'Bulk' in identifying high yielding lines (Table 1). 'Breeder+CTD' also identified more high yielding lines based on the 1999-2000 and 2000-2001 crop cycles than 'Breeder-only' selection, although this was not consistent across all crosses. This superiority of the 'Breeder+CTD' selection likely reflects wider genetic diversity compared to 'Breeder-only' selection, as the segregating populations were less severely truncated (Figure 1).

Table 1. Yields of three selection methods of germplasm flows: 'Breeder', 'Breeder+CTD,' and 'Bulk'; adjusted means from three years of yield trials.

Method	Mean yield (kg/ha)	N	Tukey grouping
Breeder	7311	57	A
Breeder+CTD	7120	154	AB
Bulk	6872	25	B

Figure 1. Number of lines identified and yield by three selection methods of germplasm flows: 'Breeder,' 'Breeder+CTD,' and 'Bulk' (modified from van Ginkel et al., 2004).



A second positive contribution of CTD to selection was the identification of very high yielding lines. This can be seen in Figure 1, where the upper tail of the 'Breeder+CTD' distribution extends beyond that for 'Breeder.' Clearly, 'Breeder+CTD' allowed very high yielding lines to be identified. However, while the top yielding lines of both methods were statistically similar—not unexpected, given breeder involvement in both—the real impact of CTD was in the identification and elimination of lower yielding lines that would otherwise have entered into expensive yield trails.

Conclusions

Clearly CTD is significantly correlated with yield under well-watered and fertilized production conditions. Although the breeder using visual selection only will make steady progress in raising yield potential, it is evident that integrating CTD in this process will improve the rate of genetic progress. CTD also improves the cost efficiency of wheat breeding, as low yielding genotypes that appear agronomically attractive can be eliminated earlier in the selection process. The only limitations are the need for clear sunny skies if accurate CTD assessments are to be made, and the timing of CTD assessment, as some genotypes differentiate best if measurements are made preanthesis and others postanthesis.

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Source and Sink Traits that Impact on Wheat Yield and Biomass in High Production Environments

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Summary

For many years, yield improvement reported in wheat was associated with increased dry matter partitioning to grain, but more recently, increases in above-ground biomass have indicated a different mechanism for achieving yield potential. The most likely way of increasing crop biomass is by improving radiation use efficiency (RUE), while there is evidence that sink strength is still a critical yield limiting factor in wheat; this suggests that improving the balance between source and sink (SS) is currently the most promising approach for raising yield, biomass, and RUE. Experiments were designed to establish a more definitive link between SS traits and yield, biomass, and RUE in high yield environments using progeny deriving from parents contrasting in some of those traits. The SS traits formed three main groups relating to (1) phenological pattern of the crop, (2) assimilation capacity up until shortly after anthesis, and (3) partitioning of assimilates to reproductive structures shortly after anthesis. The largest genetic gain in performance traits were associated with the second group; however, traits from the other groups were also identified as being genetically linked to improvement in performance parameters. Since many of these traits are interrelated, principal component analysis (PCA) and multiple regression were adopted with the view to discern these relationships more clearly. The trait most consistently associated with performance traits was biomass at anthesis (BMA). The PCA indicated a fairly close association among traits within this group (i.e., assimilation related traits) while those from the other two groups of SS traits (i.e., phenological and partitioning) appeared to have secondary but independent effects These conclusions were partially born out by stepwise multiple regression for individual crosses where BMA was often complemented by traits from the two other groups. Taken together the data suggest that the assimilation traits biomass in vegetative stage (BMV) and BMA have partially independent genetic effects in this germplasm and were complementary to achieving improved performance. The identification of a number of SS traits associated with yield and biomass, which both PCA and multiple regression suggest as being at least partially independent of one another, support the idea that additive gene action could be achieved by adopting a physiological trait based breeding approach where traits from different groups are combined in a single background A second breeding intervention based on these results would be in selecting progeny for BMA and BMV using spectral reflectance approaches since those traits that lend themselves to large scale screening.

Introduction

Raising genetic yield potential of crops remains an important research objective for applied scientists for a number of reasons. Year-to-year variation in yield due to unpredictable weather and biotic stresses can have major economic impacts; food security is still not guaranteed for millions of resource-poor people in both urban and rural areas. There is good evidence—in wheat, at least—that improved genetic yield potential of cultivars have impact in both favorable as well as marginal agro-ecosystems (Reynolds and Borlaug, 2006). The physiological basis of yield improvement in wheat has been reviewed by different workers (Loss and Siddique, 1994; Slafer et al., 1994; Calderini et al., 1999; Reynolds et al., 1999; Fischer, 2007). For many years most of the yield improvement reported was associated with increased dry matter partitioning to grain, while above-ground biomass was not modified (Austin et al., 1980; Kulshrestha and Jain, 1982; Calderini et al., 1995; Sayre et al., 1997). In addition, physiological determinants of biomass, especially radiation use efficiency of the crop, was apparently unchanged (Calderini et al., 1997; Fischer et al., 1998). However, more recently increases in above-ground biomass have been reported (Singh et al., 1998; Reynolds et al., 1999; 2001; Donmez et al., 2001; Shearman et al., 2005) indicating a different

Abbreviations: ANT=days from emergence to anthesis; BM=biomass at harvest; BMV=biomass vegetative stage (approximately Zadoks stage 35); BMA= biomass 5 days after anthesis (Zadoks stage 70); dBMs = growth rate (g/d) between approximately Zadoks 35 and 70; GM2 = grains/m^2; GSP = grains/spike; HI= harvest index; MAT=days from emergence to physiological maturity; PCA = principal component analysis; SPI= spike index; SPM = spike mass (g/m^2); SPS= spike size (g) shortly after anthesis; SM2=spikes/m^2; RGF = relative grainfill duration; RSG=relative spike growth duration; RUE=radiation use efficiency; SM2 = spikes/m^2; SS = source and sink; TKW = thousand kernel; YLD=yield of grain at harvest.

mechanism for achieving yield potential. Furthermore, despite the theoretical upper limit of HI, estimated at 0.60 (Austin et al., 1980), there has been no quantum improvement in partitioning since it reached *ca.* 0.50 in the mid-1980s (Fischer and Quail, 1990). Therefore, the conclusions reached previously by experts that investments in raising wheat yield potential should simultaneously focus on improving source and sink (Richards, 1996; Slafer et al., 1996) seem to be still valid.

The most likely way of increasing crop biomass is by improving RUE (Slafer et al., 1999). Various approaches for raising RUE of wheat has been the subject of review (Reynolds et al., 2000), with genetic modification of Rubisco probably the most recent (Parry et al., 2003; 2007). The theoretical limits to RUE were revised by Loomis and Amthor (1996) and, when applied to the irrigated wheat environment of the current study, suggest that significant increases in RUE are attainable (Reynolds et al., 2000). Furthermore, there is an ever increasing body of evidence that suggests sink strength is still a critical yield limiting factor in wheat (Fischer, 1985; Slafer and Savin, 1994; Abbate et al., 1995; Miralles et al., 2000; Borras et al., 2004; Miralles and Slafer, 2007) and that improving the balance between source and sink is currently the most promising approach for raising yield, biomass, and RUE (Reynolds et al., 2001; 2005; Shearman et al., 2005; Foulkes et al., 2007).

Candidate traits for improving the source/sink (SS) balance come from a number of studies. Bingham (1969) suggested that increasing the relative partitioning of assimilates to the developing spike by anthesis (i.e., spike index) might increase grain set. This was later confirmed by Austin et al. (1980) when they analyzed the physiological bases of wheat breeding improvement in the UK. In addition, works looking at the association between resources available during spike growth stage and the spike index have supported the idea (Fischer, 1985; Slafer et al., 1990; Abbate et al., 1995). Based on examination of the relationship between photoperiod and changes in relative duration of phenological phases, Slafer et al. (1996) proposed increasing the relative duration of spike growth (RSG) through manipulation of genetic sensitivity to photoperiod as a means to reach higher spike mass. Subsequent work by Miralles et al. (2000), in which duration of spike growth phase was increased through manipulation of photoperiod, showed that grain set could be increased in this way.

Another way to increase investment in spike growth would be to increase pre-anthesis RUE and, therefore, biomass at anthesis (BMA), making more assimilates available to increase spike mass. Higher dry matter partitioning to the spikes could also be a complementary alternative. Gonzalez et al. (2005) showed that photoperiod manipulation increased spike index. In addition, 7Ag.7DL translocation lines that showed improved agronomic performance over their recurrent parents and the following SS traits showed superior expression in tandem with yield (12%) and final biomass (9%): BMA (5%), spike mass (15%), and spike index (9%); RSG was not affected (Reynolds et al., 2005). In a subsequent study, BMA was increased artificially with a brief light treatment that increased the rate of biomass accumulation during spike-growth or booting stage (dBMs). The treatment was inevitably associated with increased BMA (21%), but there was a larger increase in spike mass (27%) and substantially increased RUE (10%) during grain filling (Reynolds et al., 2005). Work looking at winter wheat cultivars has also shown that pre-anthesis RUE was positively associated with yield gains (Shearman et al., 2005).

Therefore, experiments were designed to establish a more definitive link between SS traits and yield, biomass, and RUE in high yield environments using progeny deriving from parents contrasting in some of those traits. The SS traits formed three main groups relating to (1) phenological pattern of the crop (RSG and relative duration of grain filling-RGF-); (2) realized assimilation capacity up until shortly after anthesis (biomass at flag leaf emergence -BMV-, dBMs, and BMA); and (3) partitioning of assimilates to reproductive structures shortly after anthesis (spike mass, spike index, and absolute spike size). The specific objectives of the experiments were to study in three sets of random sister lines: (1) which SS traits were best associated with yield, biomass, and RUE; (2) the association among SS traits to indicate which trait combinations may result in additive gene action for agronomic performance.

Materials and Methods

Crop environment

All experiments were conducted at the CIMMYT experimental station near Cd. Obregon, northwestern Mexico (27 20°N, 109 54°W, 38 m ASL) during the spring wheat season (late November sowing and April harvest). The site is a temperate, high radiation environment; irrigation, plus appropriate weed, disease, and pest control were implemented to avoid any biotic or abiotic stresses. However, nitrogen fertilizer was applied at a rate (150 kg N/ha) which, in combination with residual soil N estimates, was designed to achieve approximately 80-90% of maximum yield potential (normally 7-8 t ha^{-1}; Sayre et al., 1997) and avoid yield losses associated with lodging.

Phosphate fertilizer was applied at a rate of 25 kg P/ha. Plants were sown as plots 5 m long and 1.6 m wide, consisting of 2 raised beds with 3 rows/bed (20 cm between rows) at a seed rate of 100 kg/ha. Plots were sown in randomized lattice designs with 2 reps on three consecutive wheat cycles. Emergence dates were 5 December 2001, 2 December 2002, and 6 December 2003. These three cycles will be referred to subsequently as the 2002, 2003, and 2004 growth cycles, respectively. A summary of weather data averaged for five different growth stages in each year is presented in (Table 1). The growth stages consisted of three periods up until anthesis (average date) of approximately equal day-degree length, and two periods during grainfilling of approximately equal day-degree length. The growth stages corresponded approximately as follows: (1) canopy establishment, (2) spike primordia, (3) rapid spike-growth, (4) first half of grainfilling, and (5) second half of grainfilling.

Table 1. Weather data averaged for different growth stages in three wheat cycles, northwestern Mexico, 2002-2004.

Growth stage and year	Air temperature (^oC)		Radiation	days	day ^{o}
	Max	*Min*	*MJ/m^2/d*		
2002 Cycle					
(Growth stage)					
1 Canopy establishment	24.9	6.4	14.3	26	407
2 Spike primordia	26.3	5.7	14.4	26	416
3 Rapid spike-growth	24.6	7.5	15.6	26	417
4 Grainfill: first half	27.5	7.6	21.7	22	386
5 Grainfill: second half	27.9	8.3	23.4	21	380
2003 Cycle					
Stage 1	25.2	7.8	14.8	26	430
Stage 2	27.7	7.9	15.3	25	445
Stage 3	27.2	11.1	15.3	23	440
Stage 4	25.3	9.0	20.4	22	378
Stage 5	29.1	9.2	24.5	20	383
2004 Cycle					
Stage 1	26.8	6.0	13.0	26	426
Stage 2	23.0	8.6	14.6	26	411
Stage 3	24.0	6.4	18.6	28	425
Stage 4	27.0	8.2	22.4	22	388
Stage 5	30.6	11.7	24.7	19	401

Agronomic and physiological measurements

Dry vegetative biomass (BMV) was estimated a few days after the last plots achieved full canopy closure (approximately Zadoks stage 35), and BMA was measured shortly (5 days) after anthesis (Zadoks stage 70) on each individual plot. These cuts consisted of the above-ground tissue from 3 rows of a 50 cm length of the bed, starting at least 50 cm from the end of the plot to avoid border effects. Fresh biomass was oven-dried at 70°C for 48 h for dry weight measurement. The trait dBMs was calculated as BMA-BMV divided by the number of days between their respective harvests. The trait spike index was estimated by randomly selecting 12 normal spike-bearing culms from biomass cuts shortly after anthesis and measuring the dry weight of the spikes and culms separately, spike index being the coefficient of the dry weights respectively. The trait spike size was the average dry weight of the 12 spikes. Trait spike mass was calculated by multiplying BMA by the spike index.

Dates of following phenological stages were estimated visually: 50% terminal spikelet stage (using binocular microscope), 50% anthesis, and 50% physiological maturity by the color of spikes. These values were used to derive two additional phenological parameters: (1) relative duration of rapid spike growth (RSG), i.e., the number of days between terminal spikelet and anthesis stages as a percentage of the number of days between crop emergence and physiological maturity; and (2) the relative duration of grainfilling (RGF), i.e., days between anthesis and maturity divided by days between emergence and maturity. After physiological maturity was reached, yield was measured by machine-harvesting a bordered area of 4.8 m^2. Prior to that, a random sub-sample of 100 spike-bearing culms was removed from each plot, dried, weighed, and threshed, so that harvest index could be estimated. Using these data and an estimate of individual kernel weight (TKW), yield components were calculated: spikes m^{-2}, grains spike^{-1} (GSP) and grains m^{-2} (GM2), and final above-ground biomass.

Radiation use efficiency was estimated for biomass shortly after anthesis and for biomass at maturity using the sum of incident photosynthetically active radiation from emergence to the day of the anthesis cut and until date of maturity, respectively, after correcting for predictable losses in light interception using the model presented by Reynolds et al. (2000). However, the correction assumes no genetic effects in early light interception or stay-green at the end of grainfilling. Differences in stay-green were not observed based on visual estimates (not shown); however, observed differences in BMV could have been the result of differences in early light interception. Nonetheless, the fact that growth rate between Zadoks 35 and 70 (dBMs) was highly correlated with estimated RUE shortly after anthesis (r=0.79) suggested that the effects of early light interception were relatively minor and that the estimated RUE values were a reasonable approximation with respect to genetic effects. Canopy temperature was measured on sunny days with an infra-red thermometer on all genotypes on three or four different occasions during boot stage and again during grainfilling, as described elsewhere.

Germplasm

Lines consisted of random F4 derived bulks from three crosses. Cross 1 was Condor/R143//Ente/Mexicali_2/3/A. Squarrosa (TAUS)/4/Weaver /5/Bacanora and 34 sister lines were studied with the parents. Cross 2 was Sonalika/Attila, and cross 3 was Sonalika/Borlaug, for which 23 sister lines and the parents were studied in each cross. Between F1 and F4 generations, the populations were managed as low density bulks without selection pressure being applied. The parents were chosen for high yield potential and for contrasts in RSG, spike index, and BMA (unpublished data).

Statistical analyses

To obtain the proportion of the total sums of squares accounted for by the genotype-by-year interaction for each trait, a combined analysis of variance was conducted with the PROC GLM procedure from SAS (SAS version 9.1.3, 2004), with all the effects, environments (years), reps within years, blocks within years and reps, genotypes and environment-by-genotype interaction (GEI), being considered as fixed effects.

Since the traits were measured in different units, we performed the PCA based on the correlation matrix using the PRINCOMP procedure from SAS, and then graphing the first two eigenvectors associated to the first two largest eigenvalues which accounted for 71% of the total variance.

The multiple regression was realized with the PROC REG procedure from SAS using the stepwise selection procedure.

Broad-sense heritabilities (h^2) for each trait were estimated over the three years as follows:

$$h^2 = \frac{\sigma^2{}_g}{\sigma^2{}_g + \frac{\sigma^2{}_{ge}}{e} + \frac{\sigma^2}{re}}$$

where r = number of repetitions, e = number of environments (years), σ^2 = error variance, $\sigma^2{}_g$ = genotypic variance, and $\sigma^2{}_{ge}$ = genotype-by-environment interaction variance. Similarly, the genetic correlation can be estimated as

$$\rho_g = \frac{\sigma_{gxy}}{\sqrt{\sigma^2{}_{gx}\sigma^2{}_{gy}}}$$

where ρ_g = genetic correlation between the traits X and Y, σ_{gxy} = genetic covariance between the traits, and $\sigma^2{}_{gx}$ and $\sigma^2{}_{gy}$ are the genetic variances for traits X and Y, respectively. The genetic covariance was estimated using the statistical property of the sum of two random variables, which states:

$$\sigma^2{}_{(x+y)} = \sigma^2{}_x + \sigma^2{}_y + 2\sigma_{xy}$$

which can be rearranged and written as

$$\sigma_{xy} = \frac{\sigma^2{}_{(x+y)} - \sigma^2{}_x - \sigma^2{}_y}{2}.$$

For both broad-sense heritability and genetic correlations, all the variance components were estimated using the PROC MIXED procedure from SAS considering all the terms in the model (environments, reps within environments, blocks within reps and environments, genotypes and genotype-by-environment interaction) as random effects.

Results

Agronomic response of germplasm

A summary of the mean agronomic response of sister lines from each of the three crosses—averaged over three cycles––is presented in Table 2. Crosses 1 and 3 had better yield performance on average, but agronomic parameters for progeny from all crosses were within the ranges to be expected from elite/elite crosses. The maximum and minimum values of any genotype (averaged over three years), considering all three crosses, are presented and support this conclusion, for example, when considering the range for harvest index, height, phenology, etc. As mentioned earlier, these trials were N managed to achieve approximately 80-90% of maximum yield potential and avoid the confounding effects of lodging, which can be considerable and certainly greater than the generally insignificant genotype x N interaction effects among contrasting but relatively high N levels in this environment (Sayre, personal communication).

Table 2. Growth parameters of random sister lines from three crosses averaged across genotypes and three growing cycles, and genotype range represented by max and min 3-year average values considering genotypes from all crosses, northwestern Mexico, 2002-2004.

	Final harvest								
	Yield dw *g/m^2*	Kernel dw *g*	Grains /m2	Harvest Index	Biomass dw *g/m^2*	RUE *g/MJ*	Spikes /m2	Grains /spike	Height *cm*
Cross 1 (n=36)	585	37.9	15,500	0.462	1,270	1.53	293	54.7	96
Cross 2 (n=25)	508	42.1	12,200	0.466	1,100	1.36	254	49.6	94
Cross 3 (n=25)	562	44.6	12,800	0.481	1,180	1.43	273	48.3	91
SE	26	1.9	931	0.013	62	†	17	3.2	2
Minimum	422	32.9	9,500	0.422	910	1.15	200	38.5	82
Maximum	685	50.5	19,500	0.517	1,450	1.78	345	65.5	101

	Phenology					Pre-harvest					
	Terminal Spikelet *days*	Anthesis *days*	Maturity *days*	RSG* *%*	RGF^ *%*	Biomass vegetative *g/m2*	Biomass anthesis *g/m2*	Growth rate spike-growth *$g/m^2/d$*	RUE pre-grainfill *g/MJ*	Spike Index	Spike mass *g/m^2*
Cross 1 (n=36)	39	81	120	0.352	0.323	328	818	19.4	1.79	0.317	256
Cross 2 (n=25)	35	75	118	0.331	0.365	244	681	17.8	1.64	0.341	228
Cross 3 (n=25)	37	75	120	0.320	0.374	256	704	18.4	1.70	0.356	247
SE	1.6	2	1	0.014	0.014	28	47	1.9	†	0.017	16.8
Minimum	30.0	68	115	0.284	0.267	185	577	15.8	1.42	0.275	196
Maximum	44.8	88	124	0.442	0.418	395	917	23.8	2.09	0.397	304

* RSG = relative duration of spike growth period.
^ RGF = relative duration of grain filling period.
† Calculated from means.

Genotype by year interaction (GEI) was significant for all parameters, and the proportion of the total sums of squares from ANOVA that were associated with GEI averaged 13% for yield and 18% for final biomass. Source/sink traits showed values similar to yield or lower, except for dBMs, which averaged 30% and was the highest of any trait. Both yield and final biomass were subject to path analsysis to determine the basis of this GEI in terms of the interaction of environmental variables with phenological stage and growth parameters; results will be presented subsequently. For reference, the actual range in duration from emergence to anthesis and relative duration between terminal spikelet and anthesis (as a proportion of the period from emergence to physiological maturity), respectively, were for Cross 1: 78-87 days, and 0.28-0.34; for Cross 2: 68-84 days and 0.27-0.41, and for Cross 3: 68-88 days and 0.27-0.42, considering average values across all three cycles.

Association of source/sink traits with performance traits

A number of different analytical approaches were taken to establish which of the SS traits were best associated with performance traits. Principal component analysis (PCA) was performed across the three cycles of the experiment for individual crosses as well as all genotypes from the three crosses together; PCA was also run for individual years using all genotypes. Genetic correlation was made of yield and final above-ground biomass with SS traits, considering crosses separately and together across years. Phenotypic correlations were made of yield, final biomass, and RUE with SS traits. Stepwise multiple regression was performed for SS traits on yield, final biomass, and RUE.

Considering the PCA across genotypes of all crosses and years (Figure 1), yield, biomass, and RUE can be seen to be associated most strongly with traits associated with assimilation, namely BMV and dBMs and, to a lesser extent, BMA. There was no apparent association with any of the phenological traits RSG, RGF, ANT, and MAT. Of the partitioning traits, only spike mass showed association with performance, spike size (g) and HI showed no association, and spike index showed a negative association. When considering PCA for individual years (combining crosses), the SS traits relating to in-season biomass estimates were consistently associated with performance traits, but when considering individual crosses, BMA showed the most consistent association. For RSG there was a consistent weak association with performance traits in all years, but its relationship with yield varied considerably when considering different crosses. The trait RGF showed a more or less reciprocal relationship to RSG. For spike index, the overall tendency considering years and crosses was for a weak negative association with yield.

Genetic correlations of SS traits with the performance traits yield and final biomass are presented in Table 3. The SS traits that were most consistently and strongly associated with performance traits were BMA, BMV, and spike mass. Interestingly, although a positive relationship was found between BMA and the length of the emergence-anthesis period, a strong association between BMA and RUE was also found (Figure 1). The trait spike index had a tendency to be negatively associated with yield but was more strongly and consistently negatively associated with final biomass. One of the phenological traits, RGF, was consistently and negatively associated with both yield and biomass; RSG showed more inconsistent results, being negative for cross 1 and positive for the other two. The trait dBMs showed inconsistent genetic correlations with yield and final biomass.

Phenotypic correlations were run between SS traits and three performance related traits—yield, final biomass, and RUE—and generally results were quite consistent with genetic correlations. Spearman correlation coefficients were significant but generally weaker than genetic correlations for BMV, BMA, and spike mass, except that BMV did not show significance for cross-2. For spike index, while the general trend was also towards a negative association with biomass and RUE, results were only significant for cross 3. The phenological trait RGF also showed negative association with performance traits but coefficients were not significant in cross 1, while RSG again showed positive association but it was not significant for any performance traits in cross 1 either. The trait dBMs showed significant positive association with performance related traits in cross 1 only. Phenotypic correlations for spike size (g) were positively associated with all three performance traits for cross 1 only. Phenotypic correlations between performance traits and canopy temperature measured both during the boot stage and during grainfilling were very highly significant.

Stepwise multiple regression was run on performance traits (yield, biomass, and RUE) using all SS traits for the three crosses; results are presented in Table 4. The SS trait BMA was involved with 8 of the 9 regression models and was the first step in 5 cases, while BMV was included in 5 models, in conjunction with BMA in 3 cases. The SS traits related to phenological pattern RGF and RSG were included in 4 and 3 models, respectively. The trait spike size (g) was included in all 3 models for cross 2 but not in the other crosses. The traits spike mass, dBMs, and spike index were included in one model each. When comparing the SS traits that were adopted among the 9 models, no strong pattern emerged except for the fact that more variation was explained for all three performance traits in crosses 1 and 2 than for cross 3, and BMA appeared to be more important in explaining variation in final biomass and RUE than it was for grain yield.

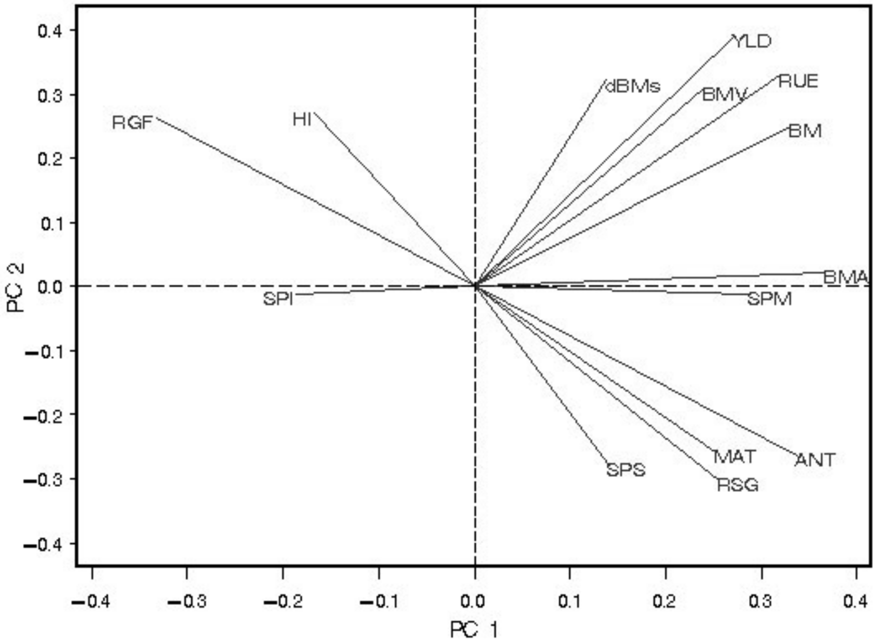

Figure 1. Principal component analysis of source/sink traits with yield and biomass considering 86 genotypes from three crosses grown over three crop cycles, northwestern Mexico, 2002-2004.

Table 3. Broad-sense heritability and genetic correlations with yield and with final biomass of source/sink traits for random sister lines of three crosses averaged over three growth cycles, northwestern Mexico, 2002-2004.

Broad-sense heritability

	RSG	**RGF**	**BMV**	**BMA**	**dBMs**	**SPM**	**SPI**
All genotypes	0.58	0.95	0.60	0.83	0.04	0.69	0.54
Avg. 3 crosses	0.37	0.92	0.49	0.77	0.18	0.70	0.44
Cross 1	0.12	0.87	0.58	0.63	0.21	0.56	0.40
Cross 2	0.50	0.97	0.40	0.87	0.12	0.81	0.45
Cross 3	0.49	0.91	0.48	0.80	0.21	0.72	0.48

Genetic correlation with yield

	RSG	RGF	BM-Veg	BM-ant	dBMs	SPM	SPI
All genotypes	0.44	-0.42	0.85	0.75	0.00	0.76	-0.26
Avg. 3 crosses	0.22	-0.30	0.67	0.67	0.40	0.53	-0.10
Cross 1	-0.16	-0.16	0.83	0.95	0.90	0.55	0.12
Cross 2	0.44	-0.47	0.33	0.57	-0.25	0.54	-0.34
Cross 3	0.37	-0.26	0.84	0.50	0.55	0.49	-0.08

Genetic correlation with final biomass

	RSG	RGF	BM-Veg	BM-ant	dBMs	SPM	SPI
All genotypes	0.55	-0.63	0.84	0.89	-0.07	0.73	-0.59
Avg. 3 crosses	0.25	-0.49	0.54	0.72	-0.18	0.67	-0.43
Cross 1	-0.44	-0.30	0.60	0.72	-0.18	0.87	-0.30
Cross 2	0.83	-0.66	0.28	0.76	-0.53	0.59	-0.62
Cross 3	0.35	-0.52	0.73	0.68	0.16	0.56	-0.37

Abbreviations used.
RSG & RGF = relative duration of spike growth and grain filling periods, respectively.
BMV & BMA = biomass at full canopy cover & anthesis, respectively.
dBMs = growth rate during spike growth period.
SPM & SPI = spike mass (g/m^2) and spike index shortly after anthesis.

An SS trait that has been reported previously as being associated with GM2 in a set of Argentinean cultivars released after 1984 (Abbate et al., 1998) is the grain number to spike dry matter ratio at anthesis. In the current study, the trait showed a similar range of genetic variation (60-100 grains/g) as observed previously and showed a 0.6 correlation with GM2 in crosses 1 and 2 while the association was reciprocal with TKW. However, the trait was not associated significantly with yield, biomass, RUE, or SS traits for any of the crosses.

Discussion

Two of the main objectives of this study were to determine which SS traits were best associated with performance parameters (yield, biomass, and RUE) and to analyze the association among SS traits to ascertain which traits in combination may result in additive gene action. Considering the three main groups of SS traits—phenological pattern; assimilation capacity up until shortly after anthesis; and partitioning of assimilates to reproductive structures—it is clear from the results that the largest genetic gains in performance traits were associated with the second group. However, traits from the other groups were also identified as being genetically linked to improvement in performance parameters. Since many of these traits are interrelated physiologically (and numerically in some cases), analytical procedures, including principal component analysis and multiple regression, were adopted with the view to discern these relationships more clearly.

Interrelationships among source/sink traits

The SS trait most consistently associated with performance traits was BMA. The PCA indicated a fairly close association among traits within this group (i.e., assimilation related traits), while those from the other two groups of SS traits (i.e., phenological and partitioning) appeared to have secondary but independent effects (Figure 1). These conclusions were partially borne out by stepwise multiple regression for individual crosses, where BMA was often complemented by traits from the two other groups, and especially the traits spike size (g) and RGF (Table 4). However, BMV was in fact the trait that most often complemented BMA in multiple regression; the PCA analysis (Figure 1) also suggested a degree of independence. Taken together, the data suggest that the assimilation traits BMV and BMA have partially independent genetic effects in this germplasm and were complementary to achieving improved performance.

Table 4. Stepwise multiple regression of source/sink traits on yield, final biomass, and radiation use efficiency for random sister lines of three crosses averaged over three growth cycles, northwstern Mexico, 2002-2004.

Yield	Step	Variables	Model R^2	F	Prob>F
Cross- 1	1	BMA	0.528	38.060	0.000
(n=36)	2	SPI	0.616	7.570	0.010
	3	RGF	0.650	3.040	0.091
	4	dBMs	0.675	2.450	0.128
Cross- 2	1	RSG	0.226	6.700	0.016
(n=25)	2	SPS	0.373	5.150	0.034
	3	BMA	0.524	6.690	0.017
Cross- 3	1	BMA	0.161	4.410	0.047
(n=25)	2	RGF	0.228	1.910	0.180
Biomass	**Step**	**Variables**	**Model R^2**	**F**	**Prob>F**
Cross- 1	1	BMA	0.619	55.140	0.000
(n=36)	2	RSG	0.643	2.280	0.140
Cross- 2	1	BMA	0.389	14.640	0.001
(n=25)	2	SPS	0.553	8.070	0.010
	3	dBMs	0.706	10.900	0.003
Cross- 3	1	BMA	0.324	11.000	0.003
(n=25)	2	SPI	0.370	1.610	0.218
	3	SPM	0.407	1.310	0.265
RUE	**Step**	**Variables**	**Model R^2**	**F**	**Prob>F**
Cross- 1	1	BMA	0.597	50.370	0.000
(n=36)	2	RGF	0.661	6.200	0.018
Cross- 2	1	BMA	0.230	6.860	0.015
(n=25)	2	SPS	0.508	12.460	0.002
	3	RGF	0.645	8.110	0.010
Cross- 3	1	BMA	0.150	4.040	0.056
(n=25)	2	SPI	0.275	3.810	0.064

Abbreviations of variables.
RSG & RGF = relative duration of spike growth and grain filling periods, respectively.
BMA = biomass shortly after anthesis.
dBMs = crop growth rate during spike growth period.
SPM, SPI, SPS = spike mass (g/m^2), spike index, & spike size (g) shortly after anthesis.

Path analysis of main effects attempts to test assumptions about causal relationships among the variables (Vargas et al., 2007). A parallel analysis reported separately (Reynolds et al., 2007) did not produce any surprises with respect to relationships among yield components, and generally confirmed the predictable relationships among SS traits. For example, BMV showed a relatively high association with BMA and spikes m^{-2}. Early vigor has been proposed as an important trait for improving yield in wheat (López-Castañeda et al., 1995). The trait dBMs showed high association with BMA and generally negative path coefficients with grains spike^{-1}—presumably reflecting compensation among yield components. Nonetheless, some results were more surprising. The trait RSG also showed a positive association with BMA, confirming the PCA result (Figure 1); this may have been associated with the fact that larger RSG was strongly associated with days to anthesis, which in turn was somewhat associated with larger BMA (see subsequent discussion). The trait BMA showed strong association with both GSP and spikes m^{-2} indicating the importance of BMA in forming two major yield components. In the light of the results of this study, RUE was one of the main causes of higher BMV and BMA. Then, BMV favored spikes m^{-2} and spike mass (associated with BMA) improved GSP. Fertile florets spike^{-1} and GSP have been shown positively associated with spike mass (Miralles et al., 2000; Gonzalez et al., 2005). In addition, spike mass was a factor in determining BMA.

However, the trait spike index, which partially defines relative spike mass, was not indicated as being involved in this relationship and, in fact, showed a surprisingly low and erratic association with other traits in general. This result was not consistent with other work indicating the importance of spike index in determination of grain number (Gonzalez et al., 2005). Although work conducted on a set of Argentinean cultivars released after 1984, while showing significant genetic variation in spike index (from 28-34%), indicated the trait was not associated with yield or grain number (Abbate et al., 1998). Association between maintenance of large numbers of grains/spike and post-anthesis assimilation rate has been demonstrated in other germplasm (Reynolds et al., 2001; 2005; Shearman et al., 2005), and preliminary evidence for a causal signaling mechanism has been suggested by studies in which abscisic levels in spike tissue at boot stage were found to be lower in genotypes displaying higher grains/spike (Figure 2).

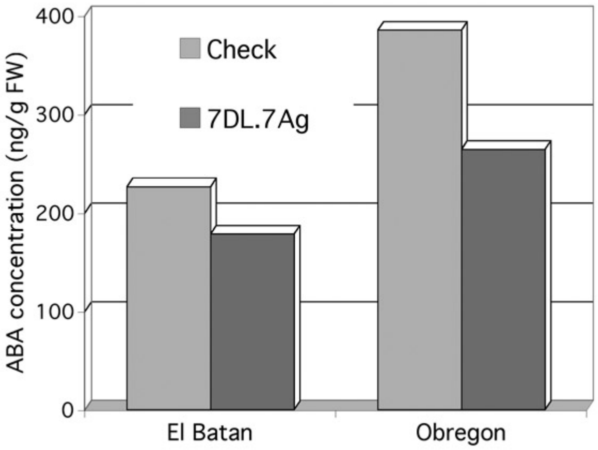

Figure 2. Concentrations of abscisic acid in spike tissue of at late boot stage of 7DL.7Ag substitution lines and their recurrent backgrounds, average of three genetic backgrounds, at two field location in Mexico 2002 (ABA was extracted using the methodology of T Setter, pers comm.).

Regulation of grain number would be an important trait to ensure seed quality in conditions where post-anthesis assimilation capacity might be reduced by a number of factors such as water deficit, shading by weeds, and loss of photosynthetic tissue due to biotic agents. It therefore is understandable if even modern wheat cultivars have retained apparently excess photosynthetic capacity (Reynolds et al., 2005), since for most of its evolution and in most environments, the crop experiences unpredictable agronomic conditions. However, the genetic capacity to partition more assimilates to spike growth (spike index) resulting in larger numbers of grains per spike and, therefore, a more complete utilization of post-anthesis photosynthetic capacity would appear to be advantageous for wheat in well managed, high yield environments. One reason why different SS traits appear to have variable influence in determining performance traits in different studies may be related to variations in phenological patterns of the lines being studied; this factor will be discussed in the section on comparing genotypes in experimental breeding populations.

Comparing genotypes in experimental breeding populations

While the timing of phenological stages such as anthesis can be controlled by choice of genotypes in studies with unrelated fixed lines, experiments aimed at estimating genetic effects of traits employ the random progeny of experimental crosses. In this kind of population data can be confounded by two major factors. The first is that some genotypes may have generally poor agronomic adaptation; however, this can be relatively easily overcome by selecting suitable populations from a range of crosses among contrasting but agronomically elite parents, as was the case in this study. The second confounding factor is genetic variation in flowering date. This is not generally considered to be problematic if the population's overall maturity class fits the target environment. However, this is almost certainly a false assumption and the most likely reason why, for example, QTL studies frequently identify *Ppd* loci as those most strongly associated with adaptation to stress environments, as has been the case for drought adaptation studies in rice (Lafitte pers comm). It is well established in wheat that key developmental processes such as kernel set are determined within relatively narrow developmental windows and can be especially sensitive to environmental conditions (Fischer, 1980; Fischer, 1985; Abbate et al., 1997). Therefore, genotypes growing side by side but which pass through key developmental stages on different dates are likely to trigger different physiological responses at the whole plant level. In summary, the potentially confounding effects of uncontrolled variation in phenology have yet to be fully overcome in studies with experimental populations aimed at identifying candidate traits and genes for crop improvement, though some progress has been reported recently (Olivares et al., 2007). The germplasm in the current study showed a 10-20 day range in days to flowering (depending on the cross) and is likely to have influenced some results. For example, while BMA was strongly correlated with RUE (Figure 1) there was also an association with the duration of the emergence-anthesis period which varied from cross to cross. There was also an association of RSG with BMA, and it appeared that larger RSG was also strongly associated with the duration of the emergence to anthesis period. Nonetheless this is the first study reported which looks comprehensively at the association of SS and performance traits and in spite of variation in phenology some very clear patterns emerge which have the potential to be applied in breeding as will be discussed in the following section.

Implications for breeding

Assuming that the genetic backgrounds chosen for this work are representative of other germplasm sources used in breeding for yield potential, these results provide a set of traits that can be applied in a number of ways. The first intervention would be in crossing, where potential parents can be screened for the SS traits and crosses made between parents with complementary characteristics. The identification of a number of SS traits associated with yield and biomass, which both PCA and multiple regression suggest as being at least partially independent of one another, supports the idea that additive gene action could be achieved by adopting a physiological trait based breeding approach where traits from different groups are combined in a single background (Reynolds and Trethowan, 2007). With reference to a conceptual model developed to identify potentially complementary traits for crossing strategies (Figure 3), the traits identified in this study fit into two main groups: pre-anthesis source traits (including BMV, BMA, and dBMs), pre-anthesis sink traits (including spike mass and spike index), and phenology traits such as RSG and RGF. The importance of post-anthesis assimilation rate probably in response to sink size was also indicated in this study by the strong association of performance traits with canopy temperature (CT) during grainfilling.

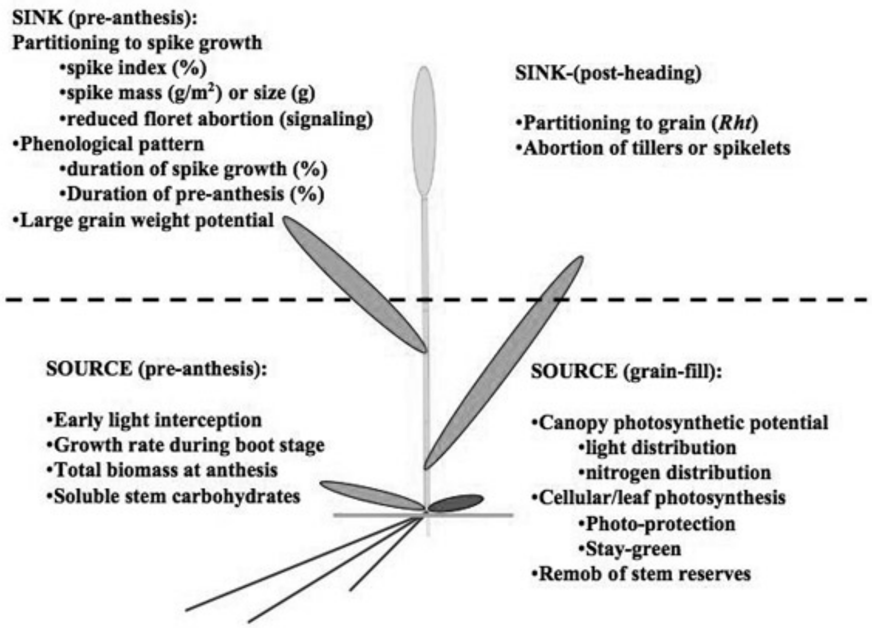

Figure 3. Conceptual model of traits influencing yield potential in wheat; traits are considered in groups that affect source or sink strength either before or after anthesis, based on evidence from the literature.

A second breeding intervention based on these results would be in selecting progeny for those traits that lend themselves to large-scale screening. It is fortuitous that BMA was identified in this study as the trait best associated with yield and biomass, since a rapid screening protocol for distinguishing genetic differences in biomass at anthesis and other crop stages such as BMV has recently been tested and validated in the same environment (Babar et al., 2006a). The methodology involves measurement of spectral reflectance indices with a hand-held probe, which also distinguishes between yield (Babar et al., 2006b). The high heritability of both BMA and BMV (Table 3) supports their value as early-generation screening traits. The third way in which the information generated by the current study could be applied to crop improvement would be to identify new and better sources of the SS traits in germplasm collections where the same rapid screening methodologies could be applied at least to screen large collections of accessions for BMV and BMA.

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Raised Bed Planting Technologies for Improved Efficiency, Sustainability and Profitability

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SUMMARY

The increase in average yield of irrigated spring wheat in farmer fields in the Yaqui Valley, from the early 1950s, when new rust resistant, non-semi-dwarf wheat cultivars were initially extended to farmers, through the development and release of the new, input responsive, high-yielding semi-dwarf cultivars up to the present, has been impressive (2.36% increase per year). However, this rate of yield improvement has gradually been decreasing to the point that there has been a rather modest yield increase in farmer fields since the 1980s. The declining yield increase trend, combined with both very minimal farmer adoption of newly released cultivars in the Yaqui Valley over the past 10 to 15 years and the apparent meagre increase in wheat genetic yield potential (especially for bread wheat) since 1992, as estimated in optimally managed yield potential trials, is troubling. This situation has led to concerns that a possible genetic yield potential "ceiling" has been or is being reached for irrigated spring bread wheat.

An important portion of the wheat yield increase that has occurred in Yaqui Valley farmer fields over the past 55 years can also be attributed to improved, crop management practices that farmers have adopted together with the new, higher-yielding cultivars. If speculation that a genetic yield potential ceiling is being reached proves correct or if continued genetic gains are going to be more difficult and expensive to realize, then one fact is patently clear – farmers now need, perhaps more than ever before, new and appropriate crop management alternatives that can maintain superior yields, reduce production costs, improve input responsiveness and offer farmers long-term, sustainable production opportunities that both protect as well as enhance the natural resource base.

Since the 1970s, most Yaqui Valley farmers have switched from planting wheat (and most other crops) on the flat with flood/basin irrigation to raised bed planting systems with furrow irrigation between the beds (however still using conventional tillage and frequent crop residue burning). INIFAP and CIMMYT scientists in collaboration with farmers in Mexico, as well as scientists/farmers in other countries, have documented the clear advantages that irrigated raised bed planting can offer and this paper outlines some of these as experienced in northwest Mexico. CIMMYT scientists have also been using the raised bed planting system as a "platform" to develop feasible permanent, raised bed, Conservation Agriculture technologies that provide opportunities to dramatically reduce tillage, manage retained crop residues on the soil surface and diversify crop rotations while offering farmers obvious and immediate production benefits and better prospects for long term sustainable crop production. This system is also described in this paper.

INTRODUCTION

Generally workshops/symposiums that focus on crop yield potential nearly always restrict considerations to genetic yield potential issues even though other factors, especially suitable crop management practices and associated agro-climatic conditions for the defined targeted area/s, also condition the expression of a crop's yield potential.

Therefore it is enlightening that this wheat yield potential symposium has included a session on "Enhancing the National Resource Foundation" although this is a rather glorified title for providing an opportunity to describe useful and sustainable crop management practices – more succinctly, suitable agronomic systems – that are appropriate for farmer use and which can help assure a more dynamic and sustainable expression of a crop's yield potential in farmer fields where it really counts.

A Retrospective View of Wheat Yield in Farmer Fields in the Yaqui Valley, Sonora, Mexico and Its Relationship with Yield Potential

There is concern that the "easy breeding" part of increasing yield potential is reaching a plateau for many crop production situations and that further major genetic gains in yield will be hard won and more costly to achieve than in the past. This concern has been expressed for the Yaqui Valley in southern Sonora, Mexico which is the historic, celebrated site associated with the origin of the wheat

"Green Revolution" and which still remains an important irrigated, spring wheat production area in Mexico. It also represents nearly 40% of the developing world's spring wheat area (Bell *et al,* 1995) including comparable areas in India, Pakistan, Afghanistan, China, Iran and southeast Turkey, among others.

Fortunately, there exists a reliable data base for the Yaqui Valley that has documented the progression of average wheat yields in farmer fields from the early 1950s when "land races" were being replaced by the new, improved, non-semi-dwarf varieties developed by Dr. Borlaug and his colleagues up through the release of the first semi-dwarf cultivars (both bread and durum wheat) that subsequently followed, to the present.

Figure 1 presents this progression of average wheat yields in farmer fields in the Yaqui Valley from 1951 to 2005. Although the overall increase in yield averaged 81 kg $^{-ha}$ per year (2.36% per year) over this entire time period is commendable, examination of Figure 1 clearly indicates that the annual increase in yield has been slowing, especially since the mid-1970s. This most certainly has contributed to suspicions that it is becoming "harder" to continue to achieve major, consistent increases in irrigated spring wheat yield potential. And it is very likely that similar, decelerating wheat yield trends (start fast but slow down with time) are occurring for many other production situations (particularly other irrigated spring wheat areas) following the initial replacement of old cultivars with a progression of modern, high-yielding semi-dwarf cultivars.

Figure 1. Wheat yield trend in farmer fields from 1951 to 2005 i the Yaqui Valley of Sonora, México.

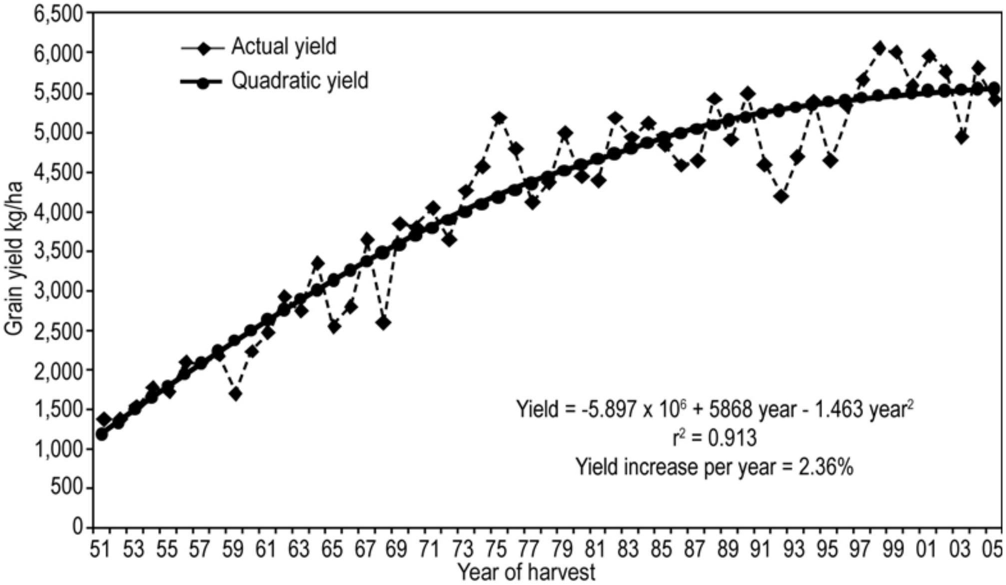


Table 1 breaks down the rate of yield increase for defined time periods associated with successive eras of cultivar development by breeders from 19951 to 2005. It is of interest to note that the highest annual percent yield increase as well as a high kg $^{-ha}$ per year increase occurred from 1951 to 1966, which corresponds to the period when improved, rust resistant, non-semi-dwarf cultivars were being supplied to farmers. Then the time period from 1966 to 1981 represents the initiation of the "grand semi-dwarf cultivar phase" distinguished by the introduction and continued improvement of the new-fangled, semi-dwarf cultivars. Marked increases in annual yields, both on a percentage basis as well on an absolute kg/ha/year basis, occurred during this era.

For the period from 1981 to 1996, the improvement in wheat yields in farmer fields dramatically slowed down, even though a fairly wide spectrum of new and supposedly higher-yielding cultivars was available for farmer adoption. One conjecture put forward by breeders about this "slow down" in yield increase is that it reflects their efforts to incorporate other needed traits (disease resistances and quality factors, among others) into the existing, high-yielding, semi-dwarf genetic platforms and that this breeding effort to consolidate other needed traits may have hindered the breeders' ability to concurrently continue to select for increased yield potential.

This speculation may explain at least part of observation of low yield gains in farmer fields from 1981 to 1996 (Table 1). But the continuing flat (even slightly negative) trend in farmer yields for the period from 1996 to 2005 does add to the persistent concerns that a "yield potential ceiling" is being encountered. However, when the yield trend for the period from 1981 to 2005 is considered, it presents a slightly better image of the situation indicating a 0.8% annual yield increase (44 kg $^{-ha}$ per year). However, it must be pointed out that little of this yield trend can be attributed to genetic gain since there was very little farmer adoption of new cultivars from about 1990 or so to about 2004.

Table 1. Annual rates of increase in average wheat yield in farmer fields in the Yaqui Valley, Sonora, Mexico for defined time periods from 1951-2005.

Time period	Periods of Cultivar Development	Yield increase per year (%)	Yield increase per year (kg/ha)	R2 Year vs Yield
1951-2005	From the first improved non-semi-dwarfs to the present	2.36	81	0.857
1951-1966	Improved non-semi-dwarfs	5.20	110	0.808
1966-1981	First generation semi-dwarfs	3.00	111	0.569
1981-1996	Second generation semi-dwarfs	0.15	9	0.011
1996-2005	Further semi-dwarf cultivar development with modest farmer adoption	-0.43	-23	0.040
1981-2005	Second generation semi-dwarfs to the present	0.08	44	0.337

During the era from 1996 to 2005 (and even back to the early 1990s, there was a remarkable reluctance by Yaqui Valley farmers to adopt new cultivars, although new, cultivars of both bread and durum wheat were regularly released. The stagnant, even declining yields from 1996 to 2005 may have occurred primarily because only two cultivars, released in the mid-to-late 1980s (Altar 84, durum wheat and Rayon 89, bread wheat, with Altar 84 predominating), occupied most of the wheat area in the Yaqui Valley during this period. The question to be answered then is "why didn't farmers replace these two varieties over such a long period"? In addition to the farmer reluctance to change cultivars during this period, there was also a very modest inclination by farmers to adopt new, high yield generating crop management practices.

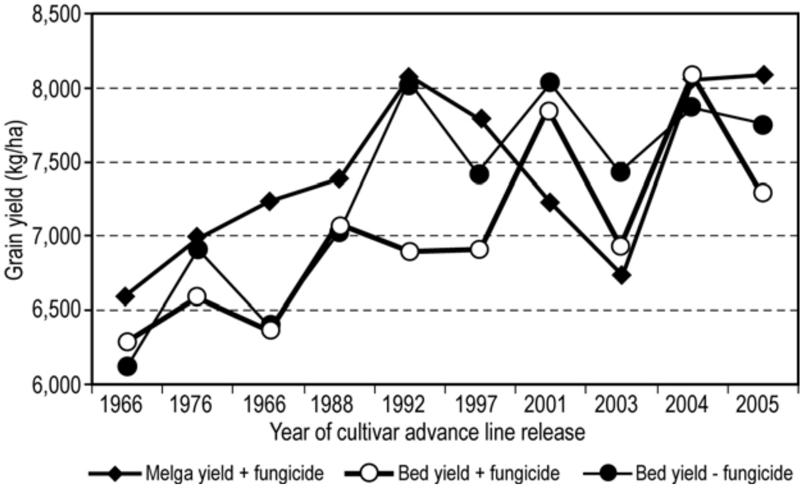
There are various possible grounds (socio-economic/marketing/trade issues, shortages of irrigation water during the last 5 years, major collapses of leaf rust resistances, especially for durum wheat cultivars, loss of soybean as a crop to rotate annually with wheat due to an newly introduced white fly biotype plus other possible factors) that may explain the lack of farmer interest to adopt new cultivars from the early 1990s to 2005, in spite of the historical readiness of Yaqui Valley farmers to adopt new cultivars almost at the drop of a hat. Therefore, it is quite conceivable that there was truly a lack of attractive, new cultivars available to farmers during this time period that combined adequate increased yield potential with the other required traits.

Part of the declining yields from 1996 to 2005 period may also, however, simply reflect the congruence of some fairly "good years" at the beginning of the era followed by several years at the end of the period with mediocre climatic conditions that limited optimum yield expression (Figure 1).

Figure 2, nevertheless, offers further evidence for negligible increase in genetic yield potential for CIMMYT derived, irrigated spring bread wheat cultivars from1992 to 2005. It presents data from the bread wheat yield potential trial conducted by the wheat agronomy group at the CIANO station during the 2004/05 crop cycle. In this trial, a historical set of bread wheat cultivars, which were released and adopted by farmers in the Yaqui Valley (and other similar areas around the world) from 1966 until 1992 were compared with newly released cultivars/advanced lines provided by the CIMMYT bread wheat breeders to include in the trial and which "theoretically" represented their best efforts for the Yaqui Valley from 1992 until 2005.

Together these two groups of lines were compared under optimum production conditions in melgas (flat planting with flood irrigation) with fungicide, on raised beds (irrigated by furrows) with fungicide and on beds without fungicide. Figure 2 clearly indicates the marked increase in genetic yield potential for the historical cultivars released between 1966 and 1992 for both melgas and beds with disease control. However, essentially no yield increase was observed for the supposedly superior lines developed after 1992 until 2005. The lack of progress in yield for bed planting without disease control for cultivars released from 1966 to 1992 reflects the erosion in their race-specific leaf rust resistance to new, evolved rust races.

Figure 2. Bread wheat yields trends for different planting systems from the 2004/05 yield potential trial.



Based on these results and especially when combined with the yield trend observed in Yaqui Valley farmer fields in Figure 1 and Table 1, it seems that there should be real concern that a possibility that a "yield potential ceiling" has been reached, at least for spring bread wheat for irrigated production situations. Therefore, until the breeders can get the irrigated spring bread wheat genetic yield potential "locomotive" back on track again, more resources and efforts to develop and extend new crop management practices to farmers which can increase yield and reduce production costs must be more earnestly emphasized.

Raised Bed Planting Technologies with Conventional Tillage – The First Step

Referring again to Figure 1 above, it goes without saying that the wheat yield increase that has occurred over the years in Yaqui Valley farmer fields has been linked with farmer adoption of superior cultivars. But this yield increase has also been combined with the parallel adoption of improved crop management practices. Bell *et al.* (1995) also focused on the Yaqui Valley and utilized the same data set that was drawn on for Figure 1, but for the period 1968 to 1990 (commencing near the initiation of the semi-dwarf cultivar phase). They concluded that during this 22 year period, 28% of the weather-adjusted yield gain was attributed to genetic gains (0.5% yield increase per year), 48% was attributed to improved crop management, mainly increased application of N fertilizer, (0.86% yield increase per year) and the remaining 24% could not be explained (0.43% yield increase per year).

One possible contribution to the unexplained portion of the yield gain from 1968 to 1990 may entail the accelerated rate of farmer adoption of conventional tilled, raised bed planting systems with furrow irrigation which replaced conventional tilled, solid-stand flat planting with flood irrigation (melgas) in the Yaqui Valley (Figure 3a and 3b). This change in planting system for wheat as well as most other crops occurred from the late 1970s up through the 1990s by which time over 90% of Yaqui Valley farmers had adopted the raised bed planting system Aquino (1998).

However, in most farmer surveys that have been conducted, increased yield has not commonly been mentioned as a primary reason for changing from planting wheat in melgas to raised beds.

Farmers more commonly tend to justify this shift in planting system based on:

- **Irrigation water savings** – Commonly 15 to over 40% irrigation water savings is observed with raised beds and furrow irrigation as compared to flood irrigation in melgas. Table 2 provides examples comparing yields for bed planting versus melga planting for various crops in a number of farmer fields in northwest India along with the irrigation water saving for raised bed planting;

- **Opportunities to use other weed control strategies besides herbicides** – Raised bed planting of wheat provides the field access opportunity to mechanically cultivate in the furrows which is now a common weed control practice used by farmers for wheat in the Yaqui Valley which, when combined with pre-seeding irrigation, has dramatically reduced the need for herbicide use in wheat by farmers in the Yaqui Valley Aquino (1998). Aquino (1998) further indicated that over 80% of farmers used herbicides in the mid-to-late 1970s when flat planting with flood/basin irrigation was widely used as compared to less than 20% current farmer use of herbicides now that more than 90% of farmers seed wheat in raised beds. In addition, bed planting allows much easier hand weeding in wheat as compared to traditional planting of wheat in solid stands on the flat because the reduced number of well-defined rows on the top of the bed which allows easier differentiation of grass weeds from wheat – a marked benefit for small-scale, resource constrained farmers;

- **New options to reduce tillage** – Many farmers directly seed crops like soybean and occasionally maize after wheat using the same beds without additional tillage. However, following harvest of these crops tillage, normal tillage is used prior to seeding the subsequent wheat crop on newly formed beds (Opportunities to further reduce tillage are more fully discussed below);

- **Opportunities for better fertilizer management, especially N fertilizers** – Raised bed planting also provides enhanced field access opportunities to place fertilizer, especially N fertilizers, when and where the wheat crop can make more efficient use. Figures 4 and 5 clearly indicate the beneficial effects obtained by band incorporation of N fertilizer at 1st node and/or boot stage on both durum yield and grain protein content, respectively. Split, banded N applications at these stages in wheat is greatly facilitated by bed planting;

- **Reduced seed rates** – Table 3 compares grain yield at 100 kg seed/ha versus 50 kg for several bed planted bread wheat genotypes. There was no significant difference in average yield at these contrasting seed rates although there were seed rate by genotype interactions.

- **Reduced lodging incidence** – Average percent plot area lodged over two crop cycles at CIANO for 16 genotypes planted in melgas was 43% versus 21% for raised beds;

- **Better stand establishment and reduction of periodical waterlogging caused by extreme rain events or excessive irrigation due to the drainage opportunity provided by the furrows between the bed.**

Figure 3a. Flat planted, flood/basin planting (melgas)

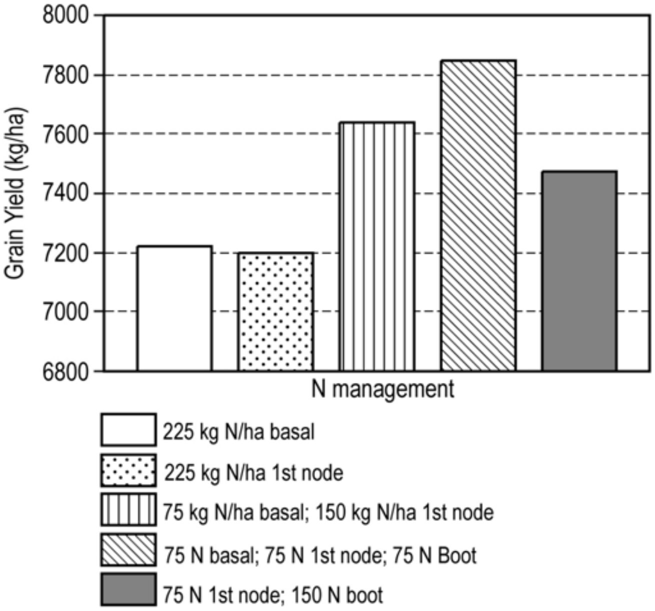
Figure 3b. Raised bed planting with furrow irrigation

Table 2. Comparison of yields and irrigation water saving for several crops with conventional till raised bed planting versus conventional till melga planting northwest India.

Crops	No of Farmers 2000 to 2002	Yield (kg/ha) Bed	(% Water Saved)	Melgas
Maize	10	3270	(35.5%)	2380
Urd bean	10	1830	(26.9%)	1370
Mung bean	10	1620	(27.9%)	1330
Pigeon Pea	10	2200	(30.0%)	1500
Gram	8	1850	(27.3%)	1580
Wheat	22	5120	(26.3%)	4810
Rice	20	5620	(42.0%)	5290

The predominant farmer perception has quite correctly characterized raised bed planting as offering opportunities to reduce costs via enhanced input use efficiencies (Table 2 and Figures 3 and 4) and by providing opportunities to employ less costly field operations.

Figure 4. Effect of application timing of 225 kg N/ha on average grain yield of six durum wheat genotypes planted on beds at CIANO/Obregon from 1996 to 1999.

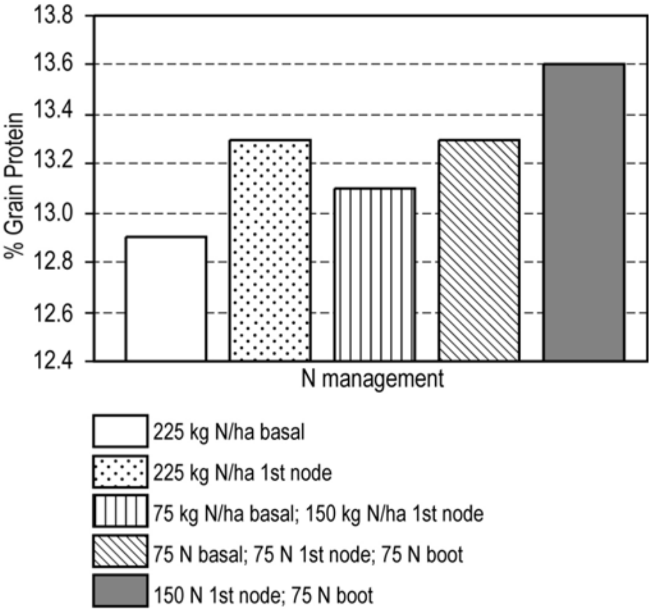


The CIMMYT wheat agronomy group has expended considerable effort to compare raised bed versus melga planting to better understand the raised bed planting system for wheat and other crops, its potential use elsewhere as well as to more fully realize the breeding implications for selection of appropriate cultivars for this planting system. Table 3 provides an example of one of these comparisons at a time when all of the included cultivars had been selected primarily by yield testing in melgas. Several interesting aspects can be observed in Table 3 including:

- The average yield for the cultivars was higher for melga planting but there was a significant planting method by cultivar interaction;
- There was no yield difference between 100 versus 50 kg.ha^{-1} seed rate for bed planting but again a significant seed rate by cultivar interaction occurred;
- Cultivars like Yecora 70 and Oasis 86 (two of the few double-dwarf gene cultivars released in the Yaqui Valley) and Super Kauz 88 were decidedly poorly adapted to bed planting due in part to short stature and/or upright growth habit. However, Borlaug 95, a short and upright cultivar, does contradict to a degree this observation;

The role of raised bed planting as a yield improving technology per se appears to be less well understood, although the reduced lodging associated with raised bed planting can directly enhance yield as well as indirectly augment yield through reduced harvest losses.

Figure 5. Effect of application timing of 225 kg N/ha on grain protein content of six durum wheat genotypes planted on beds at CIANO/Obregon from 1996 to 1999.



- Cultivars like 7 CERROS 66 performed equally well on beds at the higher seed rate but yield declined at the lower seed rate;
- BAVIACORA 92 performed equally well across all plantings systems.

Many similar trials have been conducted at the CIANO station under controlled experiment station conditions and have generally supported the premise that yield per se was not “magically” increased by bed planting. However, it became clear that there was a planting method by genotype interaction, which was largely characterized as a one-way interaction. Consequently, it has been rather easy to identify genotypes with high yields in melgas but which were low yielding when planted on raised beds. However, genotypes with high yields on beds were usually high yielding when planted in solid stands on the flat if differential lodging was not a confounding factor.

Table 3. Effect of planting method on bread wheat grain yield

Planting Method Seed Rate	Melga Planting 120 kg/ha	Bed Planting 100 kg/ha	Bed Planting 50 kg/ha
	---------------- *YIELD (kg ha^{-1})*		-------------
Cultivar			
7 CERROS 66	8273	8281	7756
YECORA 70	8177	7688	7434
CIANO 79	8059	7805	7993
SERI 82	9671	9393	8948
OASIS 86	9749	8676	8742
SUPER KAUZ 88	9763	8644	8581
BAVIACORA 92	*9767*	*9796*	*9698*
BORLAUG 95	9741	9391	9255
MEAN	9150^{a}	8709^{b}	8803^{b}

Means followed by the same letter are not significantly different by LSD (0.05); The planting method by cultivar interaction was significant at the 0.05 level and the interaction LSD (0.05) was 675 kg ha^{1}.

Understanding this interaction has allowed CIMMYT wheat breeders to dramatically replace the large areas previously managed for segregating materials and especially for yield trials in melgas over the past 15 years with raised bed planting. The advantage gained by breeders has been a striking reduction in experiment station operational costs (20 – 25% less cost per ha for bed planting compared to melgas – similar to that realized by farmers – combined with the opportunity to reinforce this saving by being able to plant up to 30% more plots per ha as compared to melga planting.

One trial that was conducted over two crop cycles at the CIANO station demonstrated very interesting features for wheat grown on raised beds. Wheat breeders, who had long-term involvement in the CIMMYT bread wheat breeding effort, were asked to identify two groups of genotypes from those that had been sent out to the “real world” in the international trials from the late 1960s to the late 1980s (yield testing under melgas was still the common practice used to identify superior genotypes throughout this period). One group of genotypes included those that had been sent out and ended up being widely used by the NARS cooperators generating positive impacts. The other group of genotypes was also sent out with equal expectations but just did not make it in the real world (but not because of problems like immediate susceptibility to leaf rust, for example).

These two contrasting groups of genotypes were then grown under both melgas and raised beds during the 1999/00 and the 2000/01 crop cycles with similar, optimum production conditions including disease control. Figure 6 presents the average yield performance for the two sets of genotypes when planted in melgas and when planted on raised beds. As can be observed, the performance of both sets of genotypes in melgas was similar with a slight but insignificant advantage for the group of disappointing “real world” performers. However, when the two sets of genotypes were grown on raised beds, the group of successful “real world”, international performers yielded significantly higher compared to the disappointing performers. It seems obvious from this trial that there is some association between stable, high genotypic yield performance across diverse circumstances for genotypes that are good “bed performers”.

Field observations over the years, both on station as well as in farmer fields, have clearly indicated that the “good” bed performers tend to “execute” excellent yields when production conditions are optimum but also produce better yields when production conditions are suboptimal (poor stand establishment, poor weed control, inadequate N and water etc). Therefore it seems likely that as farmers in the Yaqui Valley began to rapidly switch from melgas to raised bed planting from the early 1970s onward, a part of the yield increase that was left “unexplained” by Bell *et al.* (1995) may be attributed to farmer adoption during this period of cultivars like Nacozari 76, Genero 81 and Rayon 89, all of which were both successful cultivars in different locations around the world as well as excellent bed performers. While raised bed planting clearly provided Yaqui Valley farmers with reduced production costs and opportunities for increased input use efficiency, it may have also provided opportunities for expression of higher yield especially under less than optimum production/management conditions.

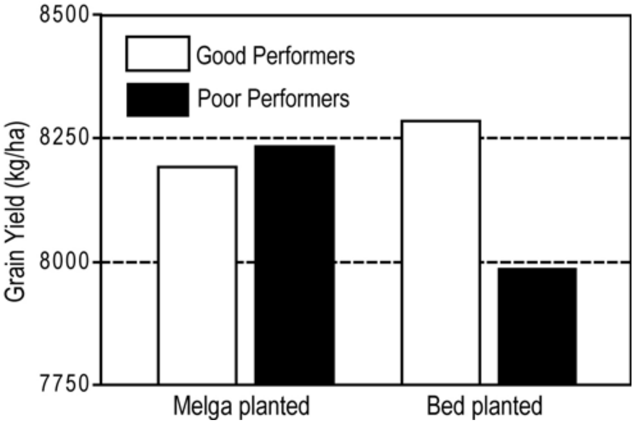
Permanent Raised Bed Planting Technologies – The Next Step

The change from conventional tilled melga planting to conventional tilled raised bed planting by farmers in the Yaqui Valley is an example of adoption of an appropriate, new “resource conserving technology”. Raised bed planting, albeit with conventional tillage, provides important opportunities for improved input use efficiency as well as various cost saving management options compared to planting in tilled melgas. However, raised bed planting as currently practiced by farmers in the Yaqui Valley still involves considerable crop residue burning (less in recent years) and tillage (again with some reduction in recent years). It does not, therefore, encompass the broad, basic tenets that characterize Conservation Agriculture (CA) which include:

- Dramatic tillage reductions with the goal to reach as close to zero till as possible across all crops that encompass a system;
- Adequate crop residue retention on the soil surface to reduce erosion and improve soil chemical (especially organic matter), physical (especially soil aggregation) and positive biological parameters (promotion of beneficial organisms);

- Economical options for potential diversification of current, repetitive crop rotations;
- Enhanced, readily perceivable economic/household benefits to encourage rapid farmer adoption while providing realistic prospects for long-term, sustainable crop production.

Figure 6. Comparison of average yields of 17 "good" bread wheat international performers versus 7 "poor" performers when planted in melgas versus beds at CIANO, during the 1999/00 and 2000/01 crop cycles (LSD at 0.05 = 239 kg/ha).



Therefore, over the past 15 years, CIMMYT agronomists (and others in various locations including India, Central Asia, China, Turkey, Australia and the USA) have endeavored to use conventionally tilled, raised bed planting as a “platform” to develop a new surface irrigated production system that complies with the basic CA tenets. This new system is called permanent raised bed planting with furrow irrigation between the beds. CIMMYT agronomists strongly believe that this new system is the logical way to bring CA to most surface irrigated production systems (wheat-cotton, wheat-maize, wheat-oilseed; wheat-legume among many others including rice-wheat).

Progress has been made in various regions/cropping systems to apply zero till planting on the flat, particularly for sprinkle irrigated conditions but also for flood irrigated conditions, including the magnificent example of farmer adoption of zero till wheat planting on the flat with flood irrigation in the Indo-Gangetic Plains (IGP) for the predominant, rice-wheat system. Unfortunately, farmer adoption of zero till for rice in the IGP is still low, reducing the consolidation of improved, beneficial soil affects, although efforts to develop appropriate zero till rice technologies are well underway.

As can be observed in Table 2, there definitely is scope for use of raised bed planting within the rice-wheat system, including planting the rice crop on beds, which can lead to irrigation water saving, better nutrient management, new weed control options and new opportunities for crop diversification within this monotonous cropping system if farmer appropriate technologies and cultivars can be developed.

CIMMYT advocates bed widths from 60 to 90 cm (furrow to furrow) for both tilled as well as permanent raised beds, especially for small-scale farmers using 2-wheel tractors or low hp, 4-wheel tractors. However, in Australia and the USA, it is common to see bed widths up to 2 m or wide for irrigated conditions and even wider beds for rainfed conditions where waterlogging is an issue and the raised beds (tilled and permanent) are mainly for drainage. On many soil types, however, irrigation water use efficiency can go down as bed width is increased which is one main reason CIMMYT agronomists do not recommend beds wider than 90cm except when appropriate for specific cropping situations.

To initiate the permanent bed planting system, a last cycle of conventional tillage to form new beds is carried out, which are then reshaped as needed and reused for successive crops. It is not a zero till system since there is soil disturbance in the furrow bottoms during the reshaping process. But there is no soil disturbance on top of the beds where crops are planted. Therefore permanent raised beds can be categorized as a controlled tillage system. For proper execution, all implement wheels should track in the furrow bottoms essentially providing an automatic controlled traffic system. The controlled implement wheel trafficking restricts compaction to the furrow bottoms, not where the crops are seeded on the bed tops, and in many cases this compaction in the furrow bottoms facilitates the forward and lateral movement of the irrigation water thereby reducing excess downward water infiltration, especially when residues are in the furrow which can retard forward water advance through the field.

The primary objective of permanent beds is to reuse the same bed continuously and indefinitely. For example, the initial raised beds that were formed during the summer of 1992 for one of the CIMMYT long term trials at CIANO (see more below) and the subsequent permanent beds have been continuously reused twice a year until the present (28 consecutive crops). Obviously the extent of continued use of the same permanent beds, however, will largely likely depend on soil type and especially on cropping system (inclusion of sugar beets and potatoes, for example, will lead to extensive soil disturbance at harvest, perhaps requiring renewed tillage to establish a new cycle of permanent beds) and. However, experience has demonstrated that the potential to enhance and improve the soil properties associated with sustainability issues (soil chemical, physical and biological parameters) is slowed or even reversed whenever a renewed cycle of tillage is applied to form a new generation of permanent raised beds.

Therefore CIMMYT agronomists, together with scientists working in several countries are attempting to development permanent raised bed technologies, including appropriate implements, that:

- Minimize/eliminate the need for tillage on top of the beds where the crops are seeded:
- Can manage full retention of all crop residues if no other suitable residue marketing opportunities exist leaving burning as an attractive option;
- Establish the appropriate threshold crop residue levels that must be retained on the soil surface to generate needed improvements in soil properties associated with production sustainability when there are other, alternative, economical uses for the crop residues:
- Encompass a wide gamut of potential crops (cereals, grain legumes, oil seeds, industrial crops and cover crops among others) in order to offer farmers a wide range of potential options for diversifying crop rotations.

Crucial to advancing the development of appropriate CA technologies, including permanent raised beds, has been the need to focus considerable efforts to develop suitable implements, especially for use by small and medium scale farmers. Commercially available CA implements are generally too large and expensive and almost none are available that are capable of seeding onto raised permanent beds (especially small grain crops like wheat and rice) without major modifications since almost all have been developed for large-scale farmers managing large areas of flat planted rainfed crops. CIMMYT agronomists have made considerable progress in developing small-scale, inexpensive implements that are suitable for small-scale farmers.

The concept of a multi-crop/multi-use implement has guided these efforts. This concept involves the development of a single implement which can simply be reconfigured to plant conventional or zero till on the flat, plant on tilled or permanent raised beds, band apply basal and top/side-dress fertilizers and reshape permanent beds for the various crops that may comprise a diversified cropping system.

Results from CIMMYT Long Term Permanent Raised Bed Planting Trials for Irrigated Production Conditions

Figure 7 presents the wheat yield results from the main, CIMMYT long term, raised bed planting trial at CIANO ongoing since 1992. This trial compares several tillage/crop residue management practices and super-imposed on these practices are a series of N rate and application timing alternatives. The trial was set-up to include continuous wheat during the winter crop cycle with maize and soybean alternating during the summer crop cycle (an annual double crop system). The loss of soybean as a viable crop in the Yaqui Valley in 1994/1995 because of a new white fly biotype has required modifying the summer crop used and maize has been planted more frequently than originally planned. Soybean has been planted on occasion since 1995 (during the summer cycle of 2001, for example) but essentially as a cover crop. The 300 kg N/ha, 1st node treatment is presented in Figure 7 to illustrate wheat yield performance, purportedly without N limitation.

Figure 7. Effect of tillage and residue management over several years on wheat grain yield (kg/ha at 12% H_2O) when 300 kg/ha N are applied at the 1st node stage at CIANO/Cd. Obregon.

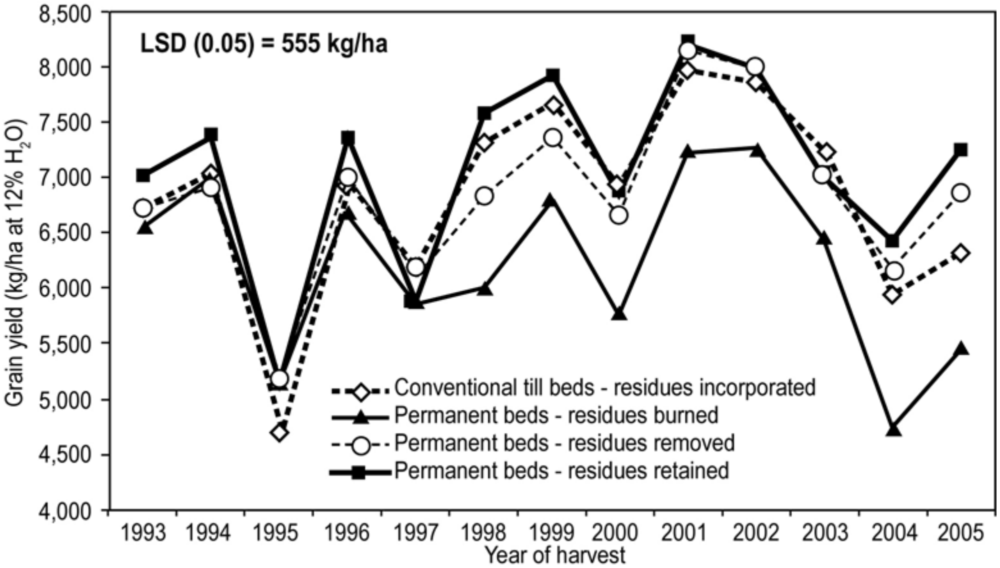


Figure 12 illustrates several important factors associated with long term trials in general and raised bed planting systems in particular including:

- During the first five wheat crops (10 crops including the summer crops) there were only very minor yield differences for the management practices. This clearly indicates why such trials need a long-term commitment. If the trial had Permanent raised beds with full surface residue retention as well as permanent beds with partial residue retention (retaining approximately 30% of residues on the soil surface yielded as well or better than conventional tilled beds with full residue incorporation. The latter practice offers a good compromise if opportunities exist for producers to use or sell crop residues.
- For the 6th wheat crop, however, all hell broke loose, especially for permanent beds where all residues had been burned. After the 6th wheat crop, wheat yield levels for the other practices tended to stabilize at similar yield levels but permanent beds with residue burning continued to follow the road to perdition.
- Permanent raised beds with full surface residue retention as well as permanent beds with partial residue retention (retaining approximately 30% of residues on the soil surface yielded as well or better than conventional tilled beds with full residue incorporation. The latter practice offers a good compromise if opportunities exist for producers to use or sell crop residues.

Figure 8 presents the average yield for these treatments at the same N level and timing for the 13-year duration of the trial. As can be observed, permanent beds with all residues burned, has a substantially lower yield compared to all other treatments. Conventional tilled beds with all residues incorporated yielded significantly lower than permanent raised beds with full residue retention of surface on the soil surface over the thirteen years with permanent beds with partial residue retention showing an intermediate yield level between these two practices.

Figure 9 compares N application timing for 150 kg N/ha, the intermediate N rate, to allow better resolution of N response. The 0 N treatment is also included for comparison. As can be observed, there are small, insignificant effects of the timing of applying 150 kg N/ha (all at basal versus all at 1st node) but permanent beds with full residue retention had higher yields, especially with the 1st node N application timing. It is also of interest to note the 0 N yield levels for the management practices. Again permanent beds with full surface residue retention had significantly higher yield indicating a more positive soil N status.

Table 4 provides some insights that help explain the yield differences between the tillage/residue management practices observed in Figures 7, 8 and 9. It presents information pertaining to the status of some chemical, physical and biological parameters that are believed to be related to soil quality/sustainable issues. Soil samples (0-7 or 0-10 cm on top of the beds) were taken in either 2002 or 2004 (10 or 12 years, respectively, after trial initiation). As can be observed in Table 4, there are minor, yet significant differences in soil organic matter with the lowest level for conventional tilled beds and the highest level for permanent beds with full residue retention. Na levels are highest for permanent beds with residues burned, followed by conventional till beds and then permanent beds with partial residue removal. Permanent beds with full residue retention have the lowest Na levels and indicate the potential benefit this system may have for use in to help ameliorate salinity in saline-prone areas.

Figure 8. Effect of tillage/crop residue management on grain yield of wheat with 300 Kg N/ha applied at first node stage averaged over thirteen years (from 1993 to 2005) at CIANO, Cd. Obregon (LSD at 0.05 = 153 kg/ha.

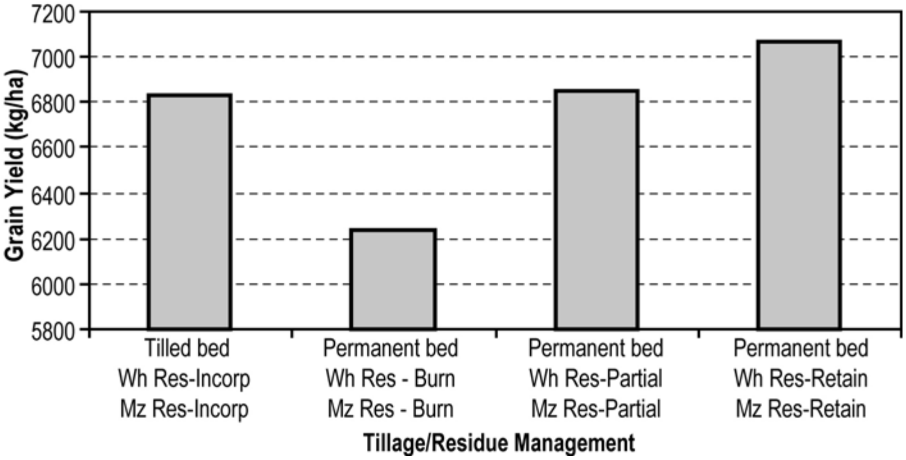


Figure 9. Effect of tillage/crop residue management and N management on wheat grain yield averaged over thirteen years (1993-2005) at CIANO, Cd. Obregon.

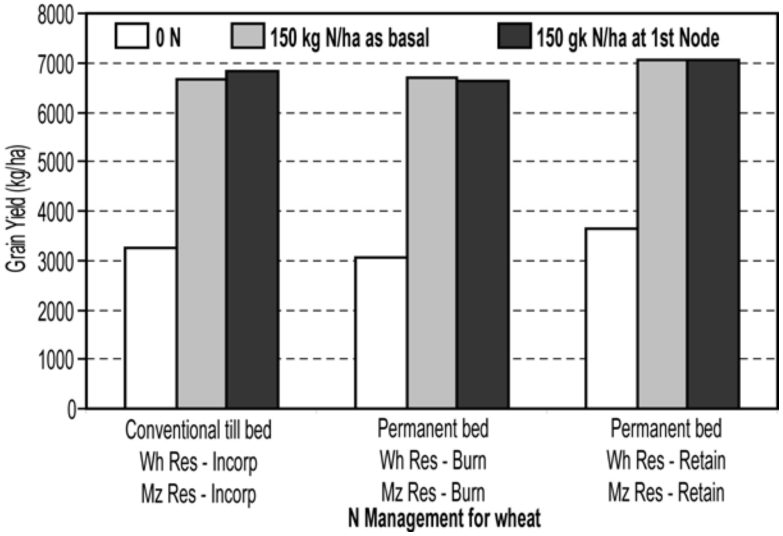


Table 4. Comparison of tillage and residue management effects for raised beds on soil chemical, Physical and biological parameters.

Tillage/Residue Management	% Org. Matter	Na ppm	Soil Dry Aggregate MWD$^{\#}$	Soil Wet Aggregate MWD$^{\#}$	SMB$^{\beta}$ C mg kg soil^{-1}	SMB$^{\Psi}$ N mg kg soil^{-1}
Conventional Till Beds Incorporate Residue	1.23	564	1.32	1.262	464	4.88
Permanent Beds Burn Residue	1.32	600	0.97	1.12	465	4.46
Permanent Beds Partial Removal of Residue For Fodder	1.31	474	1.05	1.41	588	6.92
Permanent Beds Retain Residue	1.43	448	1.24	1.96	600	9.06
Mean	1.32	513	1.15	1.434	552	6.40
LSD (P=0.05)	0.15	53	0.22	0∃.33	133	1.60

∃ - Samples for wet aggregates were collected in 2004; all others were collected in 2002; # - Mean Weight Diameter; β - Soil microbial biomass – C content; Ψ - Soil microbial biomass – N content .

Both soil dry and wet aggregates were lowest (low is bad) for permanent beds with burning all residues which probably explains the low yields for this management practice after 1997 when adequate soil degradation had occurred to negatively affect wheat yields (the straw that finally broke the camel's back). Soil wet aggregates seem to be better related to yield expression being low for permanent beds with burning, increasing for tilled beds with residue incorporation and then with permanent beds with partial residue retention with highest levels for permanent beds with full residue retention, very similar to the yield ranking in Figure 8.

Finally the soil biological parameters in Table 4 (C and N levels measured in soil microbial biomass) clearly indicate that permanent beds (with undisturbed soil on the bed surface) combined with either partial or full residue retention on the soil surface have markedly higher levels of both biological parameters as compared to tilled beds and permanent beds with residues burned. These factors also tend to parallel yield levels for the different management practices.

The suite of soil parameters that are included in Table 4 and the nature of their importance/value quite clearly support permanent raised beds with adequate retention of crop residues on the soil surface as very promising and sensible CA technology for irrigated crop production systems.

Figure 10 presents the wheat yield results from another CIMMYT long-term trial at CIANO that supports much of the above as well as providing additional information concerning bed planting. The trial was initiated in1993 but only the results from 2001 to 2004 are presented.

Similar to the results presented above in Figure 9, permanent beds with residue retention yielded dramatically better than permanent beds with residues burned and somewhat better than conventional tilled beds with all residues incorporated by the tillage.

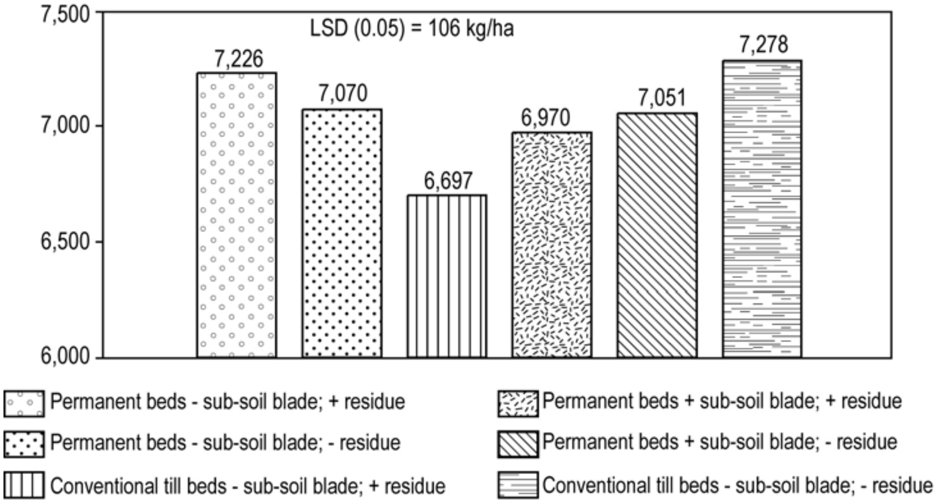
However, Figure 10 includes some additional management options. Many visitors show concerns that compaction from natural soil settling on top of the beds could be a limiting factor. To test this, small, winged sub-soil shanks, which can break potential compaction without destroying the permanent beds, were fabricated for use on top of the beds to a depth of 15-20 cm. For this trial, these miniature sub-soil shanks are used annually following wheat harvest when the soil is dry and subject to better shattering for breaking up possible compaction layers.

As can be seen in Figure 10, these shanks tended to reduce wheat yield for permanent beds with full residue retention but yield was significantly increased when the shanks were applied to permanent beds with residue burning. These results, together with those presented above as well as many other experiences from irrigated and rainfed conditions, confirm the thesis that trying to manage zero till systems with full residue removal just does not function. The many attempts by various entities in many locations (including in. Mexico) to advise farmers to adopt zero till while failing to fully understand and/or explain to these farmers the full ramifications of zero till with residue removal, largely explains most of the "zero till does not work" complaints.

The contrasting results in Figure 10 for the sub-soil shanks (reduce yield for permanent beds with residue retention on the soil surface and increase yield when residue is burned) also support the premise that well managed CA technologies perform better with no soil disturbance beyond that caused by the seeding operation itself (and even this disturbance should be kept to the absolute minimum). However, the explicit positive effect of the shanks to increase wheat yield for permanent beds with residue burning is related to the remediation of the degradation in soil properties that most likely has occurred over time from "doing the wrong thing" as was observed in Table 4.

Finally, it is of interest that conventional till beds with residue burning out-yielded tilled beds with residue incorporation (very opposite to much conventional wisdom). Another long-term trial at CIANO with eight-year duration has produced similar results. Further soil monitoring is underway to try to explain this apparent dichotomy and differential soil N dynamics are suspected to be a likely explanation.

Figure 10. Effect of Tillage and crop residue management on average bread wheat yield from 2001 to 2004 at CIANO, Cd. Obregon.*

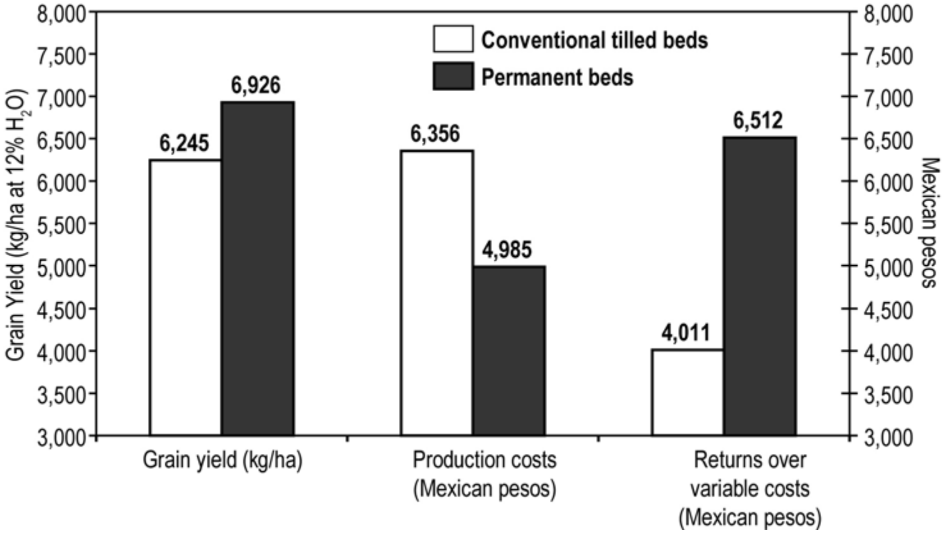


* Small scale sub-soil blade with side wings, used to about a 15-20 cm depth in the center of the bed to break possible compaction. Structure is maintained with no soil inversion.

Figure 11 provides a comparison of wheat yield, variable costs and economic returns above variable costs for conventional tilled beds with residue incorporation versus permanent raised beds with full surface retention of crop residues. In the trials described above, planting date for all management practices were within 1-3 days of each other.

In. the long term trial for Figure 16, large farm size plots are used and wheat planting after summer maize was done as soon as each management practice permitted (ranging from 7 to 14 days earlier over the years for permanent beds due to earlier field access opportunities).

Figure 11. Comparison of average wheat grain yields variable production costs and returns over Variable costs for wheat produced on conventional tilled beds versus permanent beds at CIANO, Cd. Obregon for the 2000/01 to 2003/04 crop cycles.



This explains a part of the markedly higher yield for the permanent beds in Figure 11. When this higher yield is combined with the 22% lower variable costs for permanent beds, then the economic returns over variable costs were dramatically higher for permanent beds (over 60% higher) averaged over the four years included in the analysis.

CONCLUSIONS

It would seem adamantly clear, based on the above results and discussion, that raised bed planting systems offer many positive features for farmers to both improve input use efficiency and reduce production costs for irrigated cropping systems. It is a technology that can be applied by all farmers, including small and medium scale farmers, when appropriate equipment are developed and made readily available and farmers are made aware of the technology (most efficiently by direct farmer participation in the testing and modifying the technology for their conditions).

Permanent raised beds provide a suitable technology to insure the application of CA to surface irrigated production systems while offering opportunities to reduce production costs and increase economic returns with the added benefit of assuring a more sustainable production base compared to the existing widely used conventionally tilled systems. And with the development of functional implements, suitable crop management practices and appropriate cultivars, the permanent raised bed planting system can for nearly all surface irrigated production situations.

One issue seems patently obvious. Farmers will always require superior and sustainable crop management practices irregardless of the cultivars they choose to grow. Similarly, all cultivars will be better able to achieve their genetic yield potential if farmers can apply superior and sustainable management practices. Given the widespread reductions in the allocation of resources to applied crop management (agronomy) efforts by most NARS and IARCS, it would appear that it is time to rethink priorities especially if the genetic yield potential "locomotive" truly is slowing down as appears to be the case for many crop production situations.

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Avenues to Increase Yield Potential of Short Season, High Latitude Wheat in Northern Kazakhstan and Siberia

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Summary

In the short-season, high-latitude areas of Northern Kazakhstan and Siberia, yield potential is limited by lack of moisture in the dry years and by leaf rust in years with sufficient precipitation. Three main approaches would be required to maximize yield in the region: improved agronomic practices, better adapted germplasm, and policy interventions, especially for the former. The authors conclude that application of zero and minimal tillage would provide a sustainable alternative to avoid the erosion caused by current management practices.

Introduction

Northern Kazakhstan and Western Siberia of the Russian Federation lie between 50 °N and 56 °N and 60 °E -95°E and have a typical continental climate (Fig. 1). Moving from south to north, the desert of Central Kazakhstan changes to steppe, where wheat cultivation starts. Further north, the steppe transitions to forest-steppe and eventually into Siberian forests. These changes in soil and vegetation are related to precipitation and temperature. Moving further north and east precipitation increases, but temperature and the frost-free period decreases. The North Kazakhstan steppe at Astana has an average yearly precipitation of 320 mm. Barnaul and Novosibirsk situated to the northeast have at least 100 mm more precipitation. Average distribution of precipitation follows certain patterns, with most rainfall coming in June-August. However, there are normally drought conditions in May and early June, and high variation in moisture availability from year to year. Rains in June are of crucial importance in yield determination. Severe winters with heavy snow allow planting only in May. Every five years, there is frost at the end of August, which limits the frost-free period to 100 or even 90 days (Kaskarbayev, 1998). The region has fertile soils ranging from chestnut in the south to chernozem and grey forest soils in the north, with a humus content of 3-4%.

Figure 1. Wheat area in Siberia and Northern Kazakhstan.

The history of wheat cultivation in Russian Siberia and Northern Kazakhstan is an example how settlers in harsh environments can successfully transform virgin land into productive agriculture. Millions of hectares of fertile soil were brought into cultivation in the area, which has an average winter temperature of -20°C. Because this region initially attracted settlers by its mineral resources, the development of industry and roads was a high priority. However, in the middle of the 20th century the region was transformed into a very important agricultural area supplying high quality grain for the local population and for the rest of the USSR. The wheat area at its maximum in the 1960s and 1970s reached 35 million ha (Morgounov et al., 2001). Recent data indicate substantial reductions, and in 2005 Kazakhstan grew close to 11 million ha of spring wheat, essentially half of the area in 1965-1975 (Table 1) (Gossen, 1998; FAO on-line database). As seen in the table, average yield does not exceed 1 t/ha, which is typical for a short-season, dry, low-input environment. Most wheat produced in Siberia and Northern Kazakhstan can be classified as a Hard Red Spring type according to the North American description. The continental climate, nutrient supply, and genotypes grown result in the production of grain with high protein (12-17%) and gluten (25-32%) content. The gluten is also characterized by good strength and elasticity, allowing it be used as component in flour mixtures with grain of medium or poor quality.

Table 1. Wheat area and yield in Kazakhstan in 1946-2005.

Years	Area (million ha)	Yield (t/ha)
1946-54	7.0	0.56
1955-64	24.6	0.70
1965-75	23.8	0.89
1976-85	25.3	0.96
1986-90	24.1	1.00
1991-95	14.9	0.80
1996-2000	10.7	0.85
2001-05	11.2	1.02

Sources: Gossen (1998) and FAO on-line database.

The disintegration of the USSR in 1991 resulted in an economic crisis and changes that affected the rural agricultural framework and wheat production enterprises. Privatization of the former collective and state farms in Kazakhstan by 2005 resulted in the establishment of relatively small private farms covering 1000-2000 ha; small cooperatives uniting several farmers and operating 5000-10,000 ha; big grain companies purchasing whole big farms and operating 100,000 ha or more. All these enterprises operate in a market environment driven by maximizing the profit per unit area. The 1990s economic crisis resulted in a sharp decrease of the wheat production area due to the abolishment of a command planned economy and the conversion to a market economy when the producers did not have the means for field operations, nor reliable wheat marketing channels. The current status of wheat production is characterized by a market environment with limited government support; conversion to modern field machinery and application of modern agronomy practices; search for better markets and wheat processing opportunities. This paper describes the possible directions for enhancement of wheat yield and production in the region through sustainable agronomy practices, new varieties, and new economic policies.

Enhancing Wheat Production through Sustainable Agronomic Practices

There are three main agronomic factors affecting the crop production system in Northern Kazakhstan and Siberia: tillage system, fallow, and choice of crops. When the virgin lands of Northern Kazakhstan and Siberia were first brought under cultivation in the mid-1950s and early 1960s, the production system was constrained by wind erosion. Plowed soils were very vulnerable to wind and resulted in tremendous dust storms. The research community developed and introduced soil conserving technology based on tillage without turning over the soil surface. However, 50 years of continuous tillage (even of the conservation type) reduced the amount of soil organic matter (Table 2) (Wall et al., in press). Water erosion remains a real threat especially on slooping fields. In some years, quick snow melt in spring causes substantial soil losses. More commonly it happens in fields with southern exposure to the sun. The current prices of diesel fuel in Kazakhstan (US$ 0.65-0.75 per liter) make tillage one of the main crop production costs. There is a need to improve the farming system through the application of more sustainable practices and, in particular, zero tillage.

Table 2. Reduction in soil organic matter content in virgin lands of Kazakhstan.

	Soil organic matter (%)		
	Virgin	Cultivated	% reduction
Common Chernozem	8.30	6.30	24
Southern Chernozem	5.30	4.22	20
Dark chestnut (Dark Kastanozem)	4.10	3.40	17

Source: Wall et al. (in press).

Due to dry climate in Northern Kazakhstan and Siberia, moisture availability is very important for crop production. There is a strong belief that summer fallow is needed to preserve and accumulate moisture. It certainly contributes to nitrogen availability for wheat, which is important in a system where N fertilizer is hardly applied. The yield penalty of wheat following wheat is 15-20% for the second crop, 20-25% for the third crop, and more than 25% for the fourth crop, depending on the severity of moisture stress (Kaskarbayev, 1998). However, current fallow management is not only unsustainable but also destructive to the soil. Ideally, 3-4 shallow cultivations are practiced in black fallow during the summer to control weeds and prevent moisture evaporation from the upper soil layer. Nevertheless, at best 1-2 cultivations are normally practiced, leaving some soil covered by weeds. There are strong arguments to abolish fallow from the rotation entirely (Suleimenov et al., 2005). Long-term experiments at Kazakh Research Institute of Grain near Astana (Shortandy) suggest that although wheat yield after fallow is higher, the average wheat yield per year of rotation is lower (Table 3) (Kaskarbayev, 1998). Continuous wheat for more than 20 years produced higher annual yields than any rotation with fallow. Conservation agriculture principles also suggest that a bare field without a crop is not a sustainable option. This gives rise to a dilemma: whether to maximize yield in a single year or optimize average yield in a sustainable manner.

Table 3. Effect of fallow on spring wheat yield in Northern Kazakhstan: 27-year averages.

Rotation[*]	**Average yield (t/ha)**
F-W	1.00
F-W-W	1.05
F-W-W-W	1.10
F-W-W-W-W	1.15
F-W-W-W-W-W	1.20
W-W-W-W-W-W	1.25

* F = fallow; W = wheat.
Source: Kaskarbayev (1998).

Wheat remains the only economically viable crop for Northern Kazakhstan. However, if fallow is eliminated, other crops should be introduced into the production system. There is a choice of possible crops that were commonly used in the past, but they do not compete with spring wheat due to higher production costs and unreliable marketing. Canola recently emerged as a higher value crop processed locally and exported to Europe. Although it is more profitable than wheat, the market for it is still limited. The situation is different in Siberia, where more crops are grown and utilized due to more diverse demands by the processing industry and consumers. This diversifies the cropping system and allows producers to increase their income. Wheat yield potential in a diversified production system could increase or decrease, depending on the preceding crop.

Over the last 5-7 years, Kazakh research institutions, international organizations (FAO and CIMMYT), and private companies have made substantial cooperative and individual efforts to test and introduce zero tillage system into Northern Kazakhstan, as summarized by Wall et al. (in press). These efforts have combined both on-station research experiments and on-farm trials and production experience. They came to the conclusion that zero tillage is a viable option for spring wheat production in Northern Kazakhstan, for it produces high, stable yields and savings in fuel and machinery costs. Figure 2 shows relative yields of zero tillage plots compared to conventional tillage over a period of five years. Yields are the same or slightly higher, with substantial environmental benefits and savings in fuel and machinery. The adoption of zero tillage in Northern Kazakhstan is progressing, though important issues are still to be addressed, including zero tillage drills, weed control, residue, and nitrogen management.

Agronomic approaches to raise wheat yield potential in Northern Kazakhstan are available but may go against soil conservation. Greater tillage intensity and practicing fallow every other year or every third year, coupled with adequate disease and pest management would produce the highest yields. But even in this case, farmers' return per unit area may not justify the yield increase, taking into consideration input and grain prices. On the other hand, aiming for the highest possible yield under dry conditions may not be the best option from an environmental viewpoint. Zero tillage with optimal residue and nitrogen management would maintain yields and protect the soil from water and wind erosion.

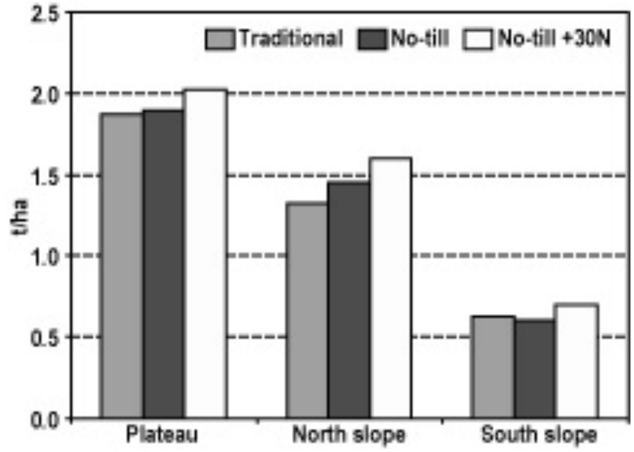

Figure 2. Average spring wheat yield over a five-year rotation period under no-till and conventional technologies, 2002-2006.

Increasing Yield through New Varieties

Gomez-Becerra et al. (2006) analyzed genotype x environment interactions of a set of 40 spring wheat varieties and breeding lines from Kazakhstan and Siberia grown across 11 locations in the region for two years. The AMMI analysis of variance for yield showed that environmental variation explained more than 70% of all variation, while varieties explained 7%, and variety x environment interaction, 15%. However, variation among sites was high, and the two years were quite different. In reality, for a particular farm or a smaller region, the role of variety is much greater. The study also identified a few varieties with wide adaptation across Northern Kazakhstan and Siberia. The study supports wide adaptation of varieties versus specific adaptation for the region. The production history shows that a few mega-varieties dominate, occupying a substantial area in the region. The landmark variety Saratov 29 at one time occupied 21 mln ha in the USSR, including Northern Kazakhstan and Siberia (Morgounov et al., 2001).

The study was based on data generated by the Kazakhstan-Siberia Network on Spring Wheat Improvement (KASIB), which includes 18 research and breeding institutions regionally and has conducted cooperative yield trials since 2000. The data demonstrated positive correlations between yield and number of days to heading. In general, the varieties grown in the region are of three maturity groups. Farmers are advised to grow varieties with different maturities to reduce risks due to unfavorable weather conditions such as early frost or drought during the crop's early growth stages. Therefore, varieties with higher yield potential are usually later maturing.

The main biotic stress for spring wheat production is leaf rust. There is a belief that a dry climate serves as a natural barrier against diseases including leaf rust. This theory is quite common among the farmers, agronomists, and the research community, including wheat breeders. However, monitoring by the Kazakh Research Institute of Crop Protection (Koyshibayev, 2002) suggests that from 1970 until 2002, there were 14 local leaf rust epidemics. The total area affected reached 4-5 million ha in Kazakhstan in some years, causing yield losses of 15-35%. Interestingly, all the varieties sown in Kazakhstan are highly susceptible to leaf rust. Only recently have new, high yielding, leaf rust resistant varieties and breeding lines been identified through KASIB testing (Table 4) (Morgounov et al., 2007). However, they still need to be formally accepted for cultivation and promoted among producers. Improvement of leaf rust resistance of spring germplasm in Northern Kazakhstan and Siberia represents the single most effective step in increasing wheat yields, especially during years with adequate precipitation.

Table 4. High yielding leaf rust resistant entries identified under natural infection through multilocational testing by KASIB Network.

Variety	Country	Breeding program location	Test year	Number of locations	Average leaf rust infection (%)	Maximum leaf rust infection (%)
Kazakhstanskaya 15	Kazakhstan	Almaty	2000-2001	5	13	20
E-736	Kazakhstan	Otar	2001	6	6	15
E-755	Kazakhstan	Otar	2001	6	7	25
Duet	Russia	Chelyabinsk	2001	6	8	25
381-MC	Kazakhstan	Aktyube	2001	6	10	20
Kvinta	Russia	Omsk	2001	6	10	25
Lutescens 71	Kazakhstan	Karabalyk	2001	6	14	20
Aria	Russia	Kurgan	2003	11	0.7	5
Lyutescens 148-97-16	Russia	Omsk	2003	11	0.8	5
Udacha	Russia	Novosibirsk	2003	11	0.8	5
Fora	Russia	Kurgan	2003	11	3	15
Sonata	Russia	Omsk	2003	11	4	20
Lyutescens 30-94	Kazakhstan	Pavlodar	2003	11	4	30
Tertsia	Russia	Omsk	2003	11	5	40
L 210-99-10	Russia	Omsk	2005	7	15	40

Starting from the mid-1990s, CIMMYT initiated broad germplasm exchange and cooperative breeding efforts with the region to enhance leaf rust resistance while maintaining general adaptation and grain quality. Testing of CIMMYT germplasm showed that its rust resistance, effective in Mexico, was also effective in Northern Kazakhstan and Siberia. Spring wheat varieties from similar environments in Canada and USA also showed good resistance in Kazakhstan. A study undertaken in 2002-2004 compared the performance of high latitude spring wheat varieties from Northern Kazakhstan/Siberia, USA, Canada, China, and Mexico (Trethowan et al., 2006a) in each respective region. A total of 30 varieties were tested in a trial, six from each group. Averages for yield and leaf rust severity for each group are presented in Table 5.

Table 5. Average yield and leaf rust severity of high latitude spring wheat varieties from different countries grown in Petropavlovsk, Northern Kazakhstan, 2002-2004.

Variety group	Yield (gr/m^2)				Leaf rust infection (%)			
	2002	2003	2004	Mean	2002	2003	2004	Mean
N. Kazakhstan/Siberia	492	217	153	287	55	59	85	66
Mexico	466	223	146	279	13	1	8	8
Canada	461	185	124	257	22	5	38	22
USA	361	177	135	225	7	0	7	5
China	326	186	126	213	34	1	19	16

Despite the high incidence of leaf rust in the North Kazakhstan/Siberia group, yield was higher compared to varieties from other countries. Most foreign germplasm, including Mexican lines, were leaf rust resistant and produced relatively high yields. Another important observation from the study was that North Kazakhstan/Siberian germplasm was taller than Canadian and US varieties and was more sensitive to day-length. Interestingly, the varieties from the region competed in yield with Canadian varieties, even in Canada. The authors of the study concluded that a breeding program based on local varieties crossed with Mexican, USA, and Canadian rust resistant germplasm would be beneficial for combining adaptation and disease resistance.

Such a program was initiated within the framework of so called “shuttle breeding” (Trethowan et al., 2006b). Crosses between Kazakh and Mexican germplasm are made in Mexico and developed until F4-F5 generations under continuous leaf rust pressure. Frequently, top crosses or three-way crosses are made utilizing the best parents from USA and Canada. The resulting populations are sent to the region to be selected for adaptation, leaf rust resistance, and other traits. The best lines identified are advanced in the breeding program, utilized in crosses, and sent back to Mexico for the next cycle of crosses. The first crosses were made in 2000; by 2006 the program had produced lines combining leaf rust resistance with high yield. The lines originating from crosses AKMOLA 2/PASTOR**,** AKMOLA 3//3/TRAP#1/YACO//BAV 92, KAZACHSTANSKAYA 10 //PASTOR1/YACO/3/BAV 92, TSELINNAYA 24//HXL7573/2*BAU exceed the yield of the local check by 10-20% while demonstrating a high degree of resistance to leaf rust.

In summary, utilization of new varieties to increase yield potential in the region is possible through incorporation of leaf rust resistance in the first place. This will protect yields during years with sufficient precipitation. The general adaptation of Kazakh and Siberian varieties is adequate and competitive with germplasm from similar environments in Canada, USA, and China. It appears that tall stature and sensitivity to day length play a positive role in yield potential. New germplasm developed by regional breeding programs as well as lines coming from the shuttle breeding program with CIMMYT offer new alternative germplasm that combines high yield with leaf rust resistance.

Current Policies that Affect Wheat Production

Kazakhstan produces more wheat grain than it consumes. Average yearly exports vary between 2-3 mln t (Morgounov and Abugalieva, 2006). The country plays a role of regional food security insurance. The government strives to play a significant role as a wheat exporter. The policies and measures undertaken support both production and exports.

The wheat grain production system in Kazakhstan remains extensive with low input use and low costs. Production costs vary between US$ 60 and 90 per ha. With an average yield of 1 t/ha and the price of grain of US$100 per ton, the average producer generates a profit of US$10-40 per ha. The main subsidies for wheat production include free crop protection against diseases and pests by the semi-government services when there is danger of an epidemic. The purchase of certified seed is supported. The farm sector in Kazakhstan needs to replace old field machinery and tractors, which represents a major expense. A government service provides subsidized credit for the purchase of machinery. Recent support includes subsidies for herbicides to replace tilled fallow with chemical fallow and encourage producers to move towards zero and minimal tillage. These supports and subsidies do not reach all producers, but enough to encourage higher yields and more profitable farming. There is no program to support replacing some of the wheat area with alternative crops.

The competitiveness of Kazakh grain on regional and world markets is limited due to the lack of access to the open seas, and the high transportation and transit costs. Efforts to negotiate lower transit costs with Russia have so far been unsuccessful. The government realizes the need for branding and promoting Kazakh grain abroad, and some measures have been taken. However, big private grain-producing and trading companies are probably more efficient in finding efficient export channels and marketing the grain. There are some sales of flour abroad, and grain producers see some potential for exporting processed wheat products. However, this has not yet reached a significant level.

Current policies in Kazakhstan provide subsidies to wheat producers and encourage higher yields and more profitable and environmentally sustainable production. The subsidies are not excessive and play a positive role in wheat production. Maintaining a free market environment and not over-regulating production and export should be important components of Kazakhstan's grain policy.

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Challenges to Wheat Production in Brazil

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Wheat production in Brazil is limited by several factors in the four different wheat breeding regions (Figure 1). The breeding regions are defined by latitude, altitude, and temperature. Acid soils, with aluminum and manganese content in excess for wheat production, are common in these breeding regions. Therefore, liming is a solution for the plow layer but sometimes insufficient due to the excess of aluminum and manganese in the subsoil. Pre-harvest sprouting, frost at flowering in the south and dry conditions in the Cerrado (Savanna) region as well as diseases caused by fungus, bacteria and virus are factors that limit the yield. The South region is the main wheat production area in Brazil (Figure 2). Over 90% of Brazilian wheat is produced in the three southermost states, Rio Grande do Sul, Santa Catarina, and Paraná (Figures 3, 4 and 5), being Paraná the main producer. Low wheat flour quality in the south, especially in the states of Rio Grande do Sul and Santa Catarina, is a constrain to increase wheat production. Yield, annual production per year, and cultivated area are indicated in Figures 3, 4, and 5, respectively.

Since its beginning in 1922, Brazilian breeding programs released 434 cultivars for different wheat production regions. During the last 30 years, Embrapa is working to select new genetic materials with better resistance to adverse environmental conditions and prevalent diseases. As a result, 115 cultivars were released by Embrapa since 1974 adapted to the different regions. Their characteristics include: dwarfing genes that confer better lodging resistance; genes for tolerance to diseases (fungus and virus) and abiotic stresses (pre-harvest sprouting and acid soils); genes that determine less responsiveness to vernalization and photoperiod duration, and better end use quality.

The research in crop rotation, no-tillage system and the use of new fungicides, associated with short and early varieties, with better harvest index and better resistance to biotic and abiotic stresses permitted to elevate the yield potential from 1,500 to 5,000 kg/ha in favorable environments. The four wheat breeding regions and the main characteristics and constrains are discussed below.

Region I – Cold, humid and high altitude

Region I has an altitude varying from 600 to 1,100 meters. The climate is subtropical to temperate and the latitude in general is higher than 24 degrees (south). Acid soils are predominant in this breeding region. In this region wheat is sown preferentially in June and July and is harvested in November and December. During the months of June, July and August, frost may occur every year. Sometimes frost also occurs in September and then it causes significant losses in yield. The region has high rainfall, frequently over 900 mm, during the growing season. In many years, most of the rain is concentrated in September, October and November, during which flowering and maturity occurs, causing pre-harvest sprouting. As a result, low gluten strength will be present in most of the years.

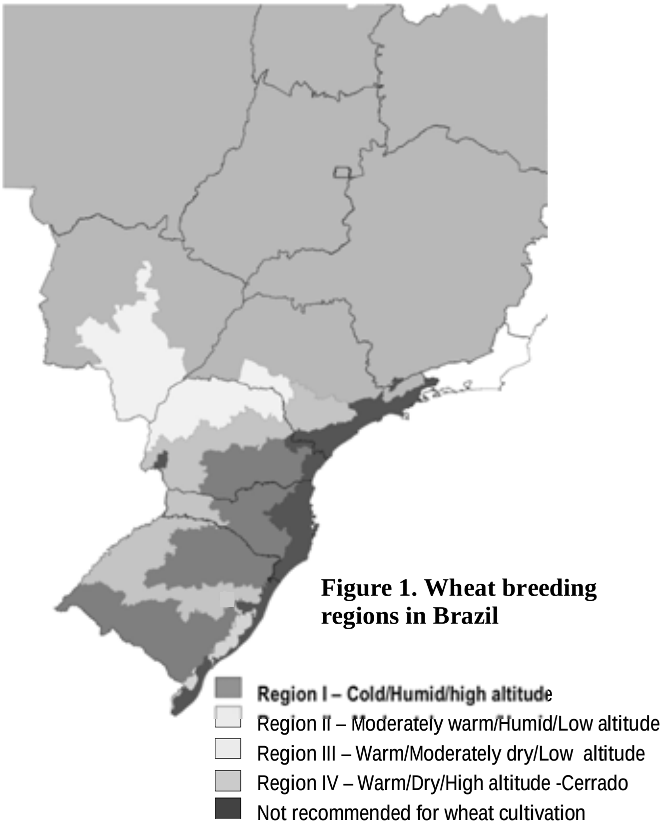

Figure 1. Wheat breeding regions in Brazil

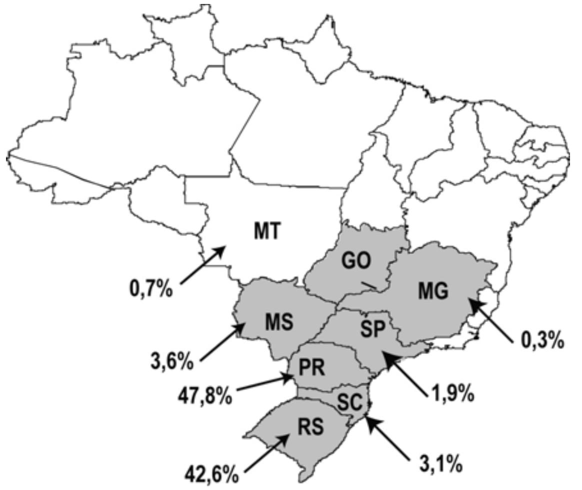

Figure 2. Percentage of wheat grain production in different states of Brazil, from 2000 to 2005. RS (Rio Grande do Sul), SC (Santa Catarina), PR (Paraná), MS (Mato Grosso do Sul), MT (Mato Grosso), SP (São Paulo), GO (Goiás), MG (Minas Gerais).

Leaf rust *(Puccinia triticina)* and scab *(Fusarium graminearum)* are the main biotic constrains. Mildew *(Blumeria graminis)*, glume blotch *(Stagonospora nodorum)*, tan spot *(Drechslera tritici-repentis)* and the virus diseases, barley yellow dwarf virus (BYDV) and soil borne mosaic virus (SBMV) are also important in most of the years.

Region II – Moderately warm, humid and low altitude

In Region II the mean altitude is lower than 600 meters. The climate is also subtropical to temperate and wheat is sown in May and harvested in October and beginning of November. Frost in late July and August and excess of rain in October are important at the maturity stage and can cause severe pre-harvest sprouting damage and losses of yield.

The main constrains are: leaf rust (*Puccinia triticina*); scab *(Fusarium graminearum*); mildew (*Blumeria graminis*); glume blotch (*Stagonospora nodorum*); tan spot (*Drechslera tritici-repentis*); spot blotch (*Bipolares sorokiniana*) (*H. sativum*); wheat blast (*Magnaporthe grisea*); virus diseases (barley yellow dwarf virus and soil borne mosaic virus); pre-harvest sprouting and acid soils.

Region III – Warm, low rainfall and low altitude

The mean altitude of Region III is about 400 meters. The climate is subtropical and wheat is sown preferentially from the end of March to the beginning of May. Harvest occurs from the end of July to the beginning of September. Scarce rainfall and low humidity in the soil are a serious problem. The soils present two situations: with and without acidity and aluminum toxicity. In the north of Paraná, the most important wheat region in Brazil, the soils in general have no aluminum and acidity limitations. In this region, wheat quality (expressed by gluten strength) is high in most years and pre-harvest sprouting is rarely present.

The main biotic constrains are: leaf rust (*Puccinia triticina*); mildew (*Blumeria graminis*); tan spot (*Drechslera tritici-repentis*); spot blotch (*Bipolares sorokiniana*) (*H. sativum*); wheat blast (*Magnaporthe grisea*); and barley yellow dwarf virus (BYDV).

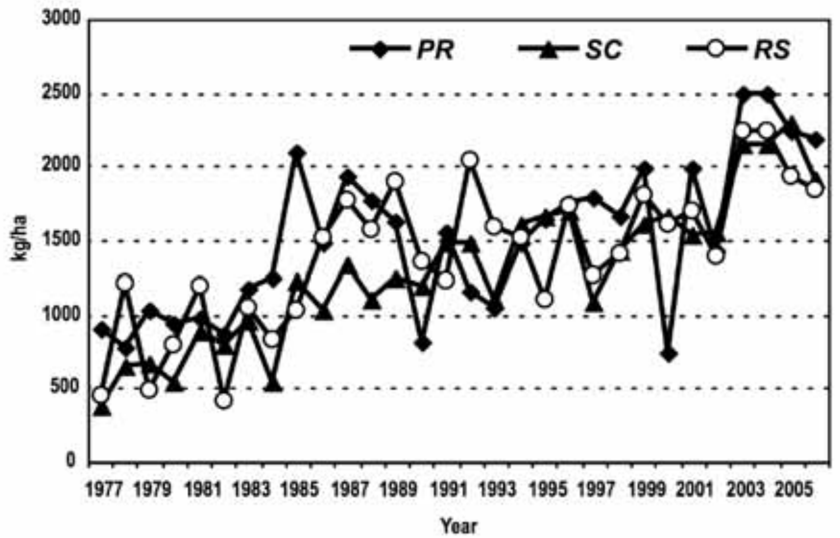

Figure 3. Mean grain yield in three states of the southern wheat region of Brazil, during the period of 1977 to 2005. RS (Rio Grande do Sul), SC (Santa Catarina), PR (Paraná).

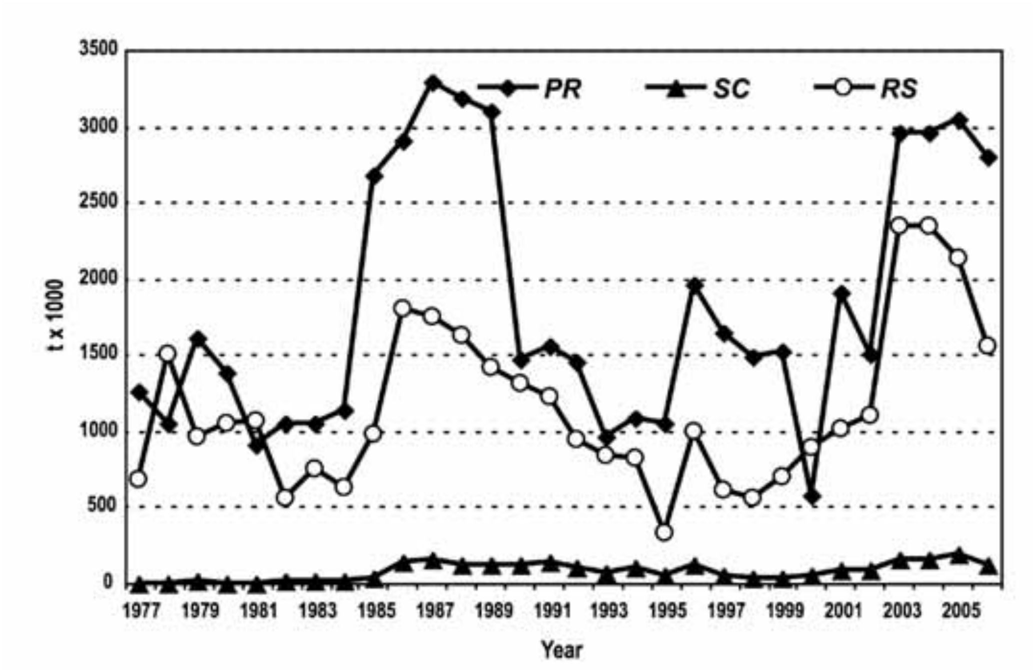

Figure 4. Wheat production in three states of the southern wheat region of Brazil, during the period of 1977 to 2005. RS (Rio Grande do Sul), SC (Santa Catarina), PR (Paraná).

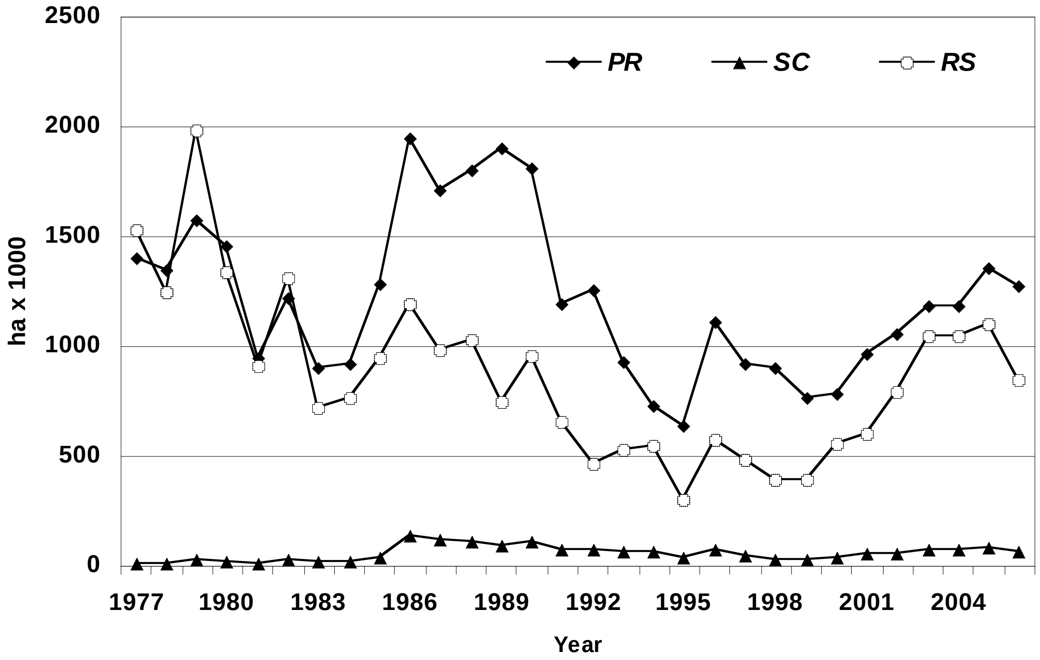

Figure 5. Wheat area in three states of the southern wheat region of Brazil, during the period of 1977 to 2005. RS (Rio Grande do Sul), SC (Santa Catarina), PR (Paraná).

Region IV – Warm & dry or Warm & Irrigated (Brazilian Savanna/Cerrado Region)

In the Brazilian Savanna region (204 million ha, in which 54% are farmland), called locally "Cerrado", soils are predominantly acid and with aluminum toxicity. It represents two environments, according to the CIMMYT mega-environments (MEs): Cerrado-ME1, where wheat is cultivated under irrigation and Cerrado-ME4 where wheat is cultivated under highly variable rainfall conditions and there is a drought period after the flowering stage. The Savanna area includes the states of Goiás, Distrito Federal, Minas Gerais and part of Mato Grosso, Mato Grosso do Sul, Bahia and São Paulo. The Cerrado wheat area is about 45,000 hectares considering both wheat (rainfed wheat sown in February to March and irrigated wheat sown in May. The production is about 180 thousand tons of grain. No-tillage predominates as a major planting process, except in some areas where wheat is cultivated after potato and other vegetable crops and farmers use conventional tillage. The major crops that compete with wheat under irrigation are common beans and corn. During the summer period the main crops under rainfed conditions are soybeans, corn, rice, and common beans.

Embrapa´s wheat breeding program main objective in the ME1 region is to increase wheat productivity, through breeding for reduced plant height and increased lodging tolerance by adding dwarf genes. Wheat blast (*Magnaporthe grisea)* and leaf blotches (*Bipolaris sorokiniana* and *Drechslera tritici-repentis*) can affect negatively yield and quality, depending on environmental conditions. In the ME4 region, important initiatives were taken to implement a breeding program for tolerance to *Magnaporthe grisea* and drought. Heat and pre-anthesis moisture stress are also the important factors limiting wheat production in the ME4 region. Bread making quality is also a very important objective for wheat breeding in both environments. Gains in yield and bread making quality were recently obtained in the Cerrado-ME1 region by the release of two spring wheat varieties by Embrapa, BRS 254 and BRS 264. BRS 254 (Embrapa 22*3/Anahuac) is better in bread making quality than Embrapa 42 and Embrapa 22 (checks). BRS 264 (Buc/Chiroca//Tui) has the combination of earliness (seven days less than Embrapa 42) and higher yield potential (5,285 kg/ha), and represents an increase in yield of 17 %, compared to the widely grown check variety Embrapa 42 (4,404 kg/ha).

BR 18-Terena (CIMMYT origin) and Aliança (has BH 1146 in the pedigree) are the best varieties for the Cerrado-ME4 region. When blast infection occurs it can reduce yield up to 80 % when fungicides are not used. The average yield from 1988 to 2004 (Figure 6) in the wheat yield trials were 1,300 kg/ha under rainfed conditions, with highly variable yields (500 to 2,500 kg/ha), depending on biotic or abiotic stresses.

The most important biotic constrains in the Cerrado region are: wheat blast (*Magnaporthe grisea*); spot blotch (*Bipolares sorokiniana*) (*H. sativum*); leaf rust (*Puccinia triticina*); mildew (*Blumeria graminis*); tan spot (*Drechslera tritici-repentis*); and barley yellow dwarf virus.

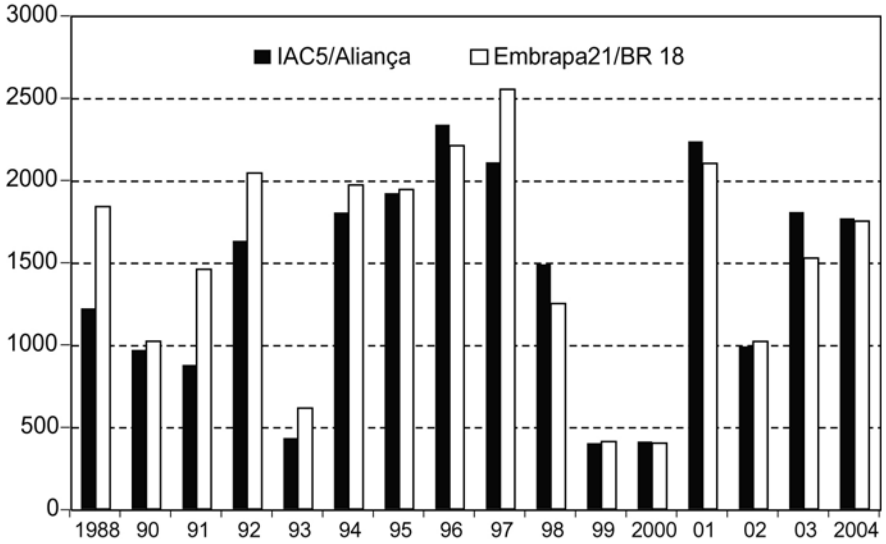

Figure 6. Grain yield (kg/ha) of the two most sown varieties across 16 years in the semiarid regional yield trial in the Brazilian Savannas, Planaltina, DF.

Improving or Preserving Bread Making Quality while Enhancing Grain Yield in Wheat

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Summary

Increasing grain production based on improved grain productivity is the main goal of wheat breeding. However, the world urban population and the demand for industrially processed foods are continuously increasing; thus a farmer would obtain a better income if his wheat crop is both highly productive and possesses the quality attributes demanded by the market. Breeders' interest in quality is greatly stimulated by the changing situation in many developing countries; in some, wheat production has become a significant component of the domestic economy, while in others farmers have started to sell their wheat grain on the export market, where quality is commonly one of the main factors determining the price of the wheat stock. To keep up with the demands of both domestic and international markets, farmers must produce high yields of wheat grain with acceptable quality. Not all wheat varieties possess the same type of quality attributes; therefore a wheat cultivar suitable for one wheat-based food type is not necessarily suitable for another food type. These quality differences result mainly from genetically-controlled grain traits such as endosperm hardness, grain protein, and gluten protein composition. These grain quality traits can be improved through breeding. However, there are non-grain factors (biotic and abiotic constraints) affecting the expression of quality. In addition, nitrogen availability during grain filling and maturation determines the amount of protein accumulated in the grain and, consequently, the expression of a genotype's inherent quality traits. Wheat quality improvement by the CIMMYT Wheat Program is a team effort; breeders, agronomists, physiologists, and cereal chemists work together to achieve high yield and high quality. The problem is tackled by combining "good quality" genes/alleles and other previously identified quality-enhancing factors, by crossing the right wheat parents. At the end of every crop cycle, several quality tests are used to screen early and late advanced lines. There is an inherent problem in attempting to improve both grain yield and grain quality at the same time, since there is an inverse relationship between high yield and high protein content. Consequently, breeders must find ways to increase one without affecting the other. One additional strategy to increase grain protein content could be to introduce protein-enhancing genes from Triticum dicoccoides *into improved wheat germplasm. These two aspects are being examined by an interdisciplinary team at CIMMYT.*

Introduction

Recent social and economic events occurring at the global level are influencing both the consumption and supply of wheat in the world. The consumption of wheat has been increasing during the last decade by about 5.6 million tons/year (Carter, 2002), mainly influenced by the continuous increases in population growth and in the migration of people from rural to urban areas, particularly in developing countries of Asia. In addition, globalization has been promoting changes in dietary patterns mainly of urban populations; for example, wheat-based foods such as Asian noodles or flat breads are now commonly consumed in Western countries, while pan breads, hamburger buns, pizza, and pasta are now common in Asia and the Middle East. Consequently, the wheat processing industry around the world is increasing its demand for wheat with specific quality attributes necessary to satisfy the processing requirements of diverse traditional and non-traditional wheat-based foods. On the other hand, several wheat-producing developing countries (e.g., Kazakhstan, Ukraine, and Turkey) are making wheat production a significant component of their domestic economy. Therefore, these countries need to develop new wheat varieties combining high yield to satisfy farmers' needs and high-quality to satisfy the demands of local consumers and the export market.

Increasing grain yield and quality at the same time is complicated by the fact that there is an inverse relationship between grain yield and grain protein content, an important grain quality trait. The grain yields achieved in exporting countries best known for high protein, high quality wheat (USA, Canada, and Australia) range between 1.8 t/ha and

2.9 t/ha. In these countries, wheat is mostly grown under rainfed conditions, sometimes under drought stress; therefore, yields are low and protein concentration tends to be high. In contrast, in countries where yield levels are much higher, such as China, Egypt, and Mexico (average yields are 3.8, 6.2, and 4.5 t/ha, respectively) (Ekboir, 2002), protein content is intermediate to low.

Given this negative relationship between grain yield and grain protein, the challenge is to develop wheat varieties with improved grain yield while improving or maintaining their grain quality. Hence, in breeding for increased yield and end-use quality, it is necessary to screen for yield-related agronomic characters as well as for end-use quality related traits more than for grain protein concentration in itself. Consequently, in the early 1990s CIMMYT began a concerted effort to increase grain yield while enhancing or maintaining grain protein and end-use quality. Fortunately, the main quality-related grain and non-grain factors influencing specific processing and end-product quality are becoming better understood (Peña et al., 2002), and therefore, breeding for yield while preserving quality is feasible.

End-use and wheat quality traits

Common wheat (*Triticum aestivum*) is used as flour (refined and whole meal) to manufacture diverse leavened and flat breads, biscuits (cookies), noodles, and other baked products. Durum wheat (*T. turgidum* var. *durum*) is milled into semolina (coarse grits) to manufacture alimentary pasta world-wide and to prepare couscous (cooked grits) in Arab countries. Some durum wheat flour is used in the production of medium-dense breads in Mediterranean and Middle Eastern countries (Quaglia, 1988; Qarooni, 1994).

Although consumption of traditional foods is still very important in the world, especially in rural areas of countries in Asia, West Asia-North Africa, and Latin America, today's urban consumers look for more healthy, nutritious foods and/or convenience foods (frozen foods, instant noodles, etc.). Newly marketed wheat-based foods, such as noodles and flat breads in Europe, the Americas, and Australia, or leavened breads and wheat-based fast foods in Asia, are easily accepted by urban populations. The wheat quality requirements to prepare (at household or village level) acceptable traditional wheat-based foods (leavened and flat breads; flour noodles, regional dishes) in rural areas are different from those required to prepare the same products at the industrial level. Better dough properties and end-product quality uniformity are usually required in the latter case. Wheat end-use quality differences result mainly from genetically-controlled traits such as endosperm hardness and gluten protein composition. These grain quality traits can be improved through breeding.

Grain hardness. Grain hardness is a quality trait associated with the milling properties of wheat, the water absorption capacity of flour, and the baking quality of the resulting dough. Grain hardness is determined by the packing of grain components in the endosperm cells. Allelic variations of the puroindoline genes (*Pina*; *Pinb*) determine the presence of a 15KD protein attached to the surface of the membrane of the starch granule; starch from soft wheat tends to have more of this protein than starch from hard wheat (Greenwell and Schofield, 1986).

Proteins. The bread making quality of wheat is determined by the combined effect of grain protein (gluten) concentration and gluten protein quality-related factors such as the size of the aggregated protein polymer and the combination of specific gluten proteins, namely glutenins (high- and low-molecular weight) and gliadins (see Weegels et al., 1996, for a review). These characteristics confer differential visco-elasticity to gluten and are the main factors explaining differences in bread making quality among wheat cultivars. HMW-glutenin, LMW-glutenin, and gliadins, which are controlled by genes present in the complex *Glu-1* (*Glu-A1; Glu-B1; Glu-D1*), *Glu-3* (*Glu-A3; Glu-B3; Glu-D3*), and *Gli-1* (*Gli-A1; Gli-B1*; *Gli-D1*), respectively (Branlard and Dardevet, 1985; Sozinov and Poperelya, 1980; see Weegels et al., 1996, for a review), can be identified electrophoretically or by the use of molecular markers; therefore, combinations of quality-desirable glutenin and gliadin subunits can be manipulated through breeding.

Breeding for Yield and Quality in Wheat at CIMMYT

A major change in CIMMYT's crossing methodology began 10-12 years ago; it involved including at least one parent (mostly males) expressing medium-strong to strong and extensible gluten in roughly 90% of all crosses. This shift was possible because CIMMYT includes genotypic information associated with gluten quality in its conventional quality-trait (phenotypic) characterization of parental stocks. At the beginning, data on HMW-glutenin subunit composition and, later, on LMW-glutenin constitution, omega gliadins, and the presence of *Sec-1*-controlled secalins from rye (associated with the quality-undesirable 1B/1R translocation) were made available for use in new crosses (Peña et al., 2004). In the remaining 10% of crosses, high yielding parents are combined to keep apace with the need for ever-increasing yield. Little quality screening is carried out in segregating populations because applying early-generation quality testing is practically impossible at CIMMYT, where two crop cycles per year are the norm. Marker assisted selection for some traits under the control of a few genes (starch properties, grain hardness, specific HMW-glutenin subunits) may be applied in the very near future to screen at the segregating stages.

In comparing indirect quality tests such as protein content, sodium dodecyl sulfate (SDS)-sedimentation, and Sedimentation Index (SDS-Sedimentation/protein concentration) to screen for desirable dough mixing properties and gluten viscoelasticity (elasticity and extensibility), it was found that truncation using protein percentage alone results in a high reduction in the selection of high yielding lines (Trethowan et al., 2001); the best selection of lines possessing desirable dough mixing and viscoelastic properties (mixograph and alveograph parameters, respectively) and high grain yield potential was achieved using the Sedimentation Index (Trethowan et al., 2001). This ratio is weighted against those genotypes producing high SDS-sedimentation values primarily on the basis of their high protein content and favors those with higher SDS-sedimentation values at lower protein levels. As protein content is influenced more by environmental factors than SDS-sedimentation, this ratio improved the heritability of selection. Therefore, the SDS-sedimentation index is used to screen lines in the late-segregating (F5) and early-advanced (F6-F7) stages of breeding. Actual screening for dough-mixing (Mixograph), dough viscoelastic (Alveograph) properties, and bread making quality is performed on advanced (F8-F9) and elite high yielding lines.

The new advanced lines resulting from this screening strategy express increased dough mixing time and stability, improved dough strength and extensibility, and increased bread loaf volume. This improvement in quality is partly explained by the increased frequency of the *Glu-D1* HMW glutenin subunit 5+10 and of several other quality-desirable LMW-glutenin alleles in newer materials. At the same time yield levels increased (up to 0.07%/year), grain protein content remained constant. Therefore, gluten protein quality, rather than its quantity, increased. The percentage of new lines expressing strong to very strong gluten type with medium to high yield rose to 20% (van Ginkel et al., 2003).

An additional strategy to increase grain protein in high yielding genotypes is the introgression of high protein genes from wheat-related species. At CIMMYT, efforts to manipulate the latter trait are already underway. To this end, crosses involving wheat possessing a major gene (located on chromosome 6B) for high protein from *T. dicoccoides* and high-yielding bread and durum wheat lines have been performed. The enhancement of grain protein concentration in high yielding levels (above 5.0 t/ha) has yet to be seen.

Environmental Effects on Protein Quantity and Quality

There are non-grain factors (biotic and abiotic) that affect the expression of inherent grain quality traits. However, important bread making quality traits such as grain hardness, glutenin and gliadin composition, and SDS-sedimentation, have high heritabilities and relatively small genotype x environment (GxE) effects (MacRitchie et al., 1990; Lukow and McVetty, 1991; Fenn et al., 1994; Peterson et al., 1998). Peterson et al. (1998) found that the variations in dough mixing properties and other baking parameters attributed to environment were greater than those associated with the genotype. In contrast, Lukow and McVetty (1991) found that genotypic variance was much greater than that of the environment for the same characters. Robert and Denis (1996) found that the Alveograph gave relatively small GxE effects for W (strength) and P (tenacity) but significantly larger effects for P/L (extensibility).

Although GxE interactions on quality traits are generally significant, they are less significant than those affecting grain yield. While location effects can be large, genotypes tend to rank similarly across locations. Therefore, screening for SDS-sedimentation, grain hardness, and grain protein can greatly assist breeders in identifying high-quality wheat lines. Even more, the SDS-sedimentation/flour protein ratio allows correction for variable protein levels associated with particular locations/fertilization regimes and correlates well with baking quality-related parameters while maintaining variability for yield potential (Trethowan et al., 2001). Therefore, while most breeding programs conduct yield evaluations over many locations, a subset of locations will provide an adequate representation of end-use quality requirements.

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Innovation Systems and Impact Pathways for Wheat

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Summary

Wheat is produced in a wide range of agroecologies and farming systems. Bread wheat, which accounts for 90% of total wheat production, is grown on a substantial scale in 69 countries on five continents. As a result, wheat underpins food security in many developing countries, providing 40% of food crop energy to rural and urban consumers. Wheat improvement, therefore, has the potential to contribute substantially to the first Millennium Development Goal (MDG) of halving hunger and poverty by 2015, as well as to several other MDGs.

The complex web of partners who contribute to the process of wheat improvement, from the development of advanced wheat lines by international researchers to the adoption of improved cultivars by farmers, can be considered as an innovation system. Generally there is at least one dominant pathway through the innovation system that carries the major part of the improved germplasm from breeders to farm fields, often resulting in higher productivity of wheat and improved farm household livelihoods. This chain represents the first half of the impact pathway. The impact pathway continues, however, with secondary effects such as farming system diversification, which often follows the intensification of wheat. Further indirect impacts of adoption and intensification are generally evident in the local nonfarm economy as a result of production and consumption linkages.

The adoption of improved cultivars is influenced on the demand side by the characteristics of the farm household system and the wheat marketing or value-adding chains from the farm to the consumer; and on the supply side by the nature and performance of the germplasm/seed delivery pathway from the breeders to the farm. Together the three elements (germplasm delivery pathway, farm household system characteristics, and the wheat value chain) can be viewed as the "U" framework, which determines the rate and magnitude of adoption. In the early stages of agricultural development, germplasm delivery pathways and value chains are barely discernible. Where agriculture is dominated by the public sector, relatively well-defined single channel delivery pathways and value chains are often observed. In marked contrast, in middle income countries with commercializing agriculture and well developed institutions, the U-framework often takes the form of webs of interacting agencies and businesses.

Introduction: Evolving Production and Markets

Slow growth in wheat production

Wheat is produced in a wide range of agroecologies and farming systems and is grown on a substantial scale, i.e., more than 100,000 hectares in 69 countries on five continents, covering some 213 million hectares worldwide in 2005 (FAO, 2006). The food security of many developing countries depends heavily on wheat, which accounts for 99.6 million of the total 446 million hectares of cereals in the developing world (FAO, 2007). About one-fifth of the global wheat area is found in low-income countries with GNI per capita of US$ 825 or less in 2004.

This section of the paper describes how there has been a gradual slowing in the growth of wheat production after peeking in the 1980s against a backdrop of rapid transformation of wheat markets and value chains. In the second section, the drivers of *adoption* of modern wheat varieties are described, including factors such as agricultural input services, farm household characteristics, and market conditions. In the third section, the discussion of drivers of adoption is placed in the context of agricultural *innovation systems* that include users, transmitters, and producers of technology and information. In the fourth section, it is argued that a full appreciation of the adoption process requires an in-depth understanding of *impact pathways* that link gene banks, breeders, farmers, and other ultimate beneficiaries.

Wheat productivity increased significantly during the past 40 years (especially in developing countries) through, *inter alia*, the availability of better varieties, more effective pest and disease control, better production practices, and improved farm management. Annual yield growth rates peaked at 2.75% p.a. in the 1980s, after widespread adoption of semidwarf varieties; since then, yield growth has slowed in part because varietal replacement is now more important than initial adoption and also because of environmental factors (Heisey, 2002). However, increased physical productivity has been offset, to varying degrees depending on location, by a substantial increase in input prices and a steady decline in grain prices. Nevertheless, genetic improvement of wheat continues to contribute to increased wheat yield and, in various ways, to the improvement of household livelihoods and the achievement of the Millennium Development Goals (MDGs), especially the first MDG of halving hunger and poverty by 2015. The contribution of wheat improvement to the MDGs is important given the slow progress toward meeting the Goals. Empirical evidence suggests that, for every 1% increase in wheat yield, poverty has been reduced by 0.5-1.0% (World Bank, 2005).

Investments in wheat improvement research in developing countries rose rapidly in real terms from the inception of the Green Revolution in the mid-1960s, but the pattern became mixed and uneven from the mid-1980s onwards (Heisey et al., 2002). One key challenge for wheat breeding in developing countries is to maintain the level of investment in the international system. Public sector research, of which the partnership between CIMMYT and the national agricultural research systems (NARSs) is an extremely significant component, has been particularly important for wheat improvement worldwide. In fact, NARSs in developing countries released about 3,000 wheat varieties between 1966 and 2005 (Lantican et al., 2005).

Several studies have shown that CIMMYT-related germplasm has made an important contribution to international wheat breeding efforts (Byerlee and Moya, 1993; Heisey et al., 2002; Evenson and Gollin, 2003; and Lantican et al., 2005) and continues to be used extensively by public wheat breeding programs throughout the developing world. The contribution of the private sector to wheat breeding efforts varies across type of wheat and regions. Beyond OECD countries, private sector releases were most significant in Eastern Europe and the former Soviet Union, East and Southern Africa, Latin America, and to a lesser extent in the Central and West Asia and North Africa (CWANA) region. Elsewhere, the private sector accounted for very few varietal releases (Lantican et al., 2005). Under these circumstances, continued support to national and international public sector wheat improvement programs and their partnerships with private sector is required (Heisey, 2002).

Changing access to markets

Food value chains are being transformed at an astonishingly rapid rate as a result of the fast growth and significant changes in the demand from expanding urban populations in developing countries (FAO, 2004). As a result of this demand, food systems can no longer be viewed simply as a way of moving basic staples from farm to local plates. Producers now often supply long and sophisticated market chains that deliver processed and branded products to mainly urban consumers (Barghouti et al., 2004). This is particularly the case with the growth and increasing concentration of supermarkets (Weatherspoon and Reardon, 2003).

As incomes rise in low and middle-income countries, consumers are shifting from traditional cereal-based diets, including wheat-based, to energy-dense diets with substantial amounts of meat, fish, and oil (Gulati et al., 2005). The demand for food quality, and for processed foodstuffs, is increasing. Meanwhile, the "supermarket tsunami" is rolling over developing regions in Latin America, Asia, and now Africa, setting private standards for quality, reliability, and timeliness (Reardon et al., 2003; Traill, 2006). The asymmetric economic relationships in such a globalizing world is aggravated by the aggressive global purchasing policies of many supermarkets, with the consequence of high levels of market risk for small producers because sources of supply can be quickly switched (Dixon et al., 2004).

Spread of Modern Varieties

Within the changing market context, the growth of wheat production has been driven to a large degree by the adoption of improved varieties. The adoption of wheat technologies and improved cultivars occurs in distinct waves or phases. Extending the framework of Gollin et al. (2005), four phases of the adoption of modern wheat cultivars can be visualized: (1) the initial adoption of input responsive modern varieties during the Green Revolution from 1965; (2) the so-called "first post-Green Revolution" input intensification phase, with increased allocative efficiency and strong yield gains; (3) the "second post-Green Revolution" input efficiency phase, as input/output prices ratios increased in many countries in the late 1980s and 1990s; and (4) the knowledge and management-intensive phase, in which knowledge and management complement and substitute for material inputs.

Building on the rapid adoption of modern wheat varieties in South Asia and Mexico in the 1960s and 1970s, successive generations of modern varieties spread and now dominate the wheat area of the world (see Figure 1). In developing countries, modern varieties were sown on 83% of irrigated and high rainfall wheat land by the late 1970s and on practically all high crop potential land worldwide by 1990.

The differing rates of adoption between regions can be explained by a variety of factors, including agricultural input services, farm household characteristics, and market conditions. Common farm-household system characteristics that determine adoption are resource base, including farm size and access to irrigation, and education levels. Empirical studies have shown that farm size is positively correlated with adoption rates of modern wheat. This may also be attributed to the fact that large farmers are likely to have more opportunities to learn about modern varieties, and are more apt to handle the risk associated with the early adoption of these varieties. Studies demonstrate a positive correlation between the level of education of the farm household head and the probability of adopting modern seed varieties (Villaume, 1977; Gamba et al., 2002; Mussei et al., 2001). It should be noted that adoption rates are not solely correlated with formal education but with informal knowledge levels, which could stem from advice from neighboring farmers or radio programs (Mussei et al., 2001; Heisey et al., 1990; Kotu et al., 2000).

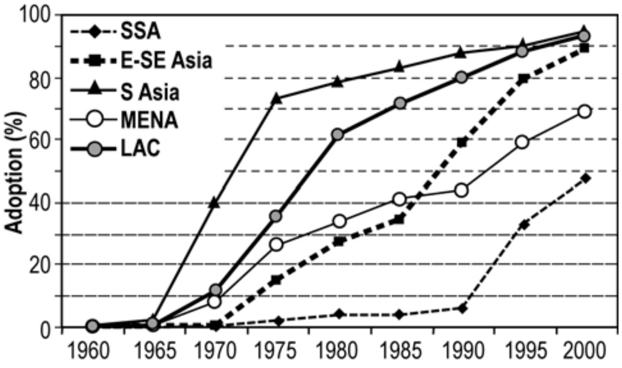

Figure 1. Adoption of modern wheat varieties by region.

On the input side, the availability of seed, agricultural information, and credit clearly influences the rate of adoption. In many countries, seed system function has been a key determinant of adoption of improved varieties. Typical lags from the release of modern wheat varieties until full adoption (usually defined as 95% of the potential coverage) range from three years for developed countries to 6.9 years for developing countries (Brennan and Byerlee, 1991). In the irrigated farming systems of the Yaqui Valley, Mexico, full adoption time is roughly 2.8 years, partly because CIMMYT manages a breeding station in the Valley, but mostly because seed multiplication and varietal distribution are very efficient and farmers in that area are progressive and often adopt new improved varieties quickly. In Kansas, the largest wheat producing state in the United States, with largely rainfed fully commercial systems, average lag until full adoption is roughly 4.1 years. While the full adoption of improved varieties is relatively fast in the commercial systems of the United States and in the irrigated commercial systems of Mexico, in the Punjab, Pakistan, and Parana, Brazil, full adoption is generally a much longer process, requiring on average 10.5 and 8.3 years, respectively. Brennan and Byerlee (1991) claim that initial adoption is a function of polices on seed multiplication and distribution and the existence of innovative farmers, whereas full adoption is a function of positive varietal characteristics and the effectiveness of the extension program of the region in question.

Extension activity, or its modern surrogates, plays an important vital role in adoption. In a review of East African adoption studies in largely rainfed semicommercial wheat farming systems, Doss et al. (2003) show that farmers' exposure to extension demonstrations of varieties and good production practices can increase adoption rates of new varieties (also see Fisher et al., 1996). Quite apart from demonstrations, access to extension agents also provides more information, which accelerates the adoption of modern varieties (Kotu et al., 2000, for rainfed farming systems in Ethiopia). It has been argued that there is a threshold level of cumulative information that must be attained before a new technology or variety is adopted. Another source of information on new varieties is farmers' membership in groups and local networks, often informally organized, which have been shown to positively influence adoption rates through the sharing of techniques and information on potential benefits and risks in Ethiopian rainfed systems (Zegeye et al., 2001) and in Turkish winter wheat systems (Demir, 1977).

Many studies show that farmers with access to credit have a higher probability of adopting modern wheat varieties than those with no access. For example, Kotu et al. (2000) concluded that the extension of credit in Ethiopian rainfed farming systems increased the probability of adoption of modern wheat varieties by non-adopters by 84.3%.

On the output side, farmers need access to wheat markets to dispose of surplus production at a reasonable price. The function of the market chain from producer to consumer, also known as the value chain, often depended on the public sector in the Green Revolution areas. In recent decades, the role of the private sector has become dominant in the wheat value chains in a majority of wheat producing countries.

Overall, agricultural policies play an important role in creating effective input and market institutions that are essential for rapid adoption. As noted in the preceding paragraphs, the adoption of improved varieties is determined by complex characteristics of, and interrelationships among farmers, and input and market institutions, which can be viewed as an agricultural innovation system.

Agricultural Innovation Systems

It is the decisions of millions of farmers worldwide that ultimately will determine whether improved wheat varieties are adopted and adapted, leading to increased productivity, improved livelihoods, other primary and secondary impacts, and reduced poverty. Therefore, agriculture can be viewed as an integrated technical-social system in which farmers and service providers create solutions to production and livelihood problems, often taking advantage of new opportunities through the modification of new technologies and existing production systems (Hall et al., 2005).

Consequently, agricultural development is an immensely complex process characterized by, *inter alia*, a high degree of nonlinearity. To target germplasm improvement more effectively, CIMMYT and its partners need a better understanding of the innovation systems and impact pathways and networks that link research outputs (germplasm and information) to farm-level impacts, including improved household livelihoods. This approach implies a shift of focus from crops to people-centered livelihoods and from linear technology transfer to a nonlinear complex systems approach to understanding how farmers innovate and systems evolve.

The interactions of partners, from the development of advanced wheat lines by researchers to the adoption by farmers, can be considered as an innovation system, comprising a web of dynamic interactions among researchers, extension agents, equipment manufacturers, input suppliers, farmers, traders, and processors (Ekboir et al., 2003; Hall et al., 2005). A generally accepted definition of innovation systems would be: a set of interrelated agents, their interactions, and the institutions that condition their behavior with respect to the common objective of generating, diffusing, and utilizing knowledge and/or technology (Spielman and von Grebmer, 2004).

An innovation system can be described in terms of three elements (Watts et al., 2003): (1) the organizations and individuals involved in generating, diffusing, adapting, and using new knowledge; (2) the interactive learning that occurs when organizations are involved in the generation, diffusion, adaptation, and use of new knowledge (and how this leads to innovation); and (3) the institutions that govern how these interactions and processes occur (since the innovation process is influenced by institutional arrangement, research on institutional development is needed as well as research on technological issues such as the generation of improved wheat germplasm).

One good example of innovation systems at work in agricultural R&D is conservation agriculture, for which public agricultural research is but one source of technology (see Seth et al., 2003). In such cases, participatory methods can be very effective in facilitating interactions among multiple stakeholders for germplasm and technology generation and adoption. One common aspect of successful development is an effective enabling environment for public-private-farmer partnerships for technology adaptation, knowledge exchange, and entrepreneurship.

One useful feature of the innovation systems concept is the emphasis on the nature of the linkages within and between researchers, extension agents, service providers, traders, farmers, and other actors. The concept also pays attention to the flow and exchange of products (e.g., germplasm) and information throughout the system. The stress on the different agendas, preferences, and demands of various actors sets the concept apart from traditional disciplinary views of research. Not all actors in an innovation system are equal in motivation or power; a dominant entity may lead the innovation network.

Useful lessons can also be drawn from the related concept and approach of agricultural knowledge and information system (AKIS), which Röling (1990) defined as “a set of agricultural organizations and/or persons, and the links and interactions between them, engaged in such processes as the generation, transformation, transmission, storage, retrieval, integration, diffusion and utilization of knowledge and information, with the purpose of working synergetically to support decision-making, problem solving and innovation in a given country’s agriculture or domain thereof.”

Applying this concept, extension has been conceptualized as one of the three pillars of an “Agricultural Knowledge and Information System for Rural Development” (AKIS/RD), together with agricultural research and agricultural education and training. The concept of AKIS/RD emphasizes the need to foster the feedback linkages between agricultural extension, research, and education. It has been adopted by the World Bank and FAO to guide policy planning and investment in these three areas (FAO/World Bank, 2000; see Rivera et al., 2005, for a review).

Agricultural innovation systems, therefore, include both users and producers of information, and must link them in a dynamic process that needs to be supported by appropriate framework conditions—not just policies, but also financial, business, and educational systems. Furthermore, because innovation typically involves a range of organizations, research organizations need to collaborate with partner organizations in order to facilitate greater innovation (Watts et al., 2003).

Wheat Impact Pathways

Often one can trace a dominant pathway through the innovation systems that carry the improved germplasm to farmers: seed is multiplied, complementary inputs *attached* and the improved germplasm reaches farmers’ fields via the germplasm delivery pathway (Douthwaite et al., 2003). This also corresponds to the first part of the impact pathway, which continues with the on-farm effects of adoption, notably the increase in yield and profit, the improvement of household food security and livelihoods, the changes in crop and livestock production patterns, such as diversification, practices, often better management, and greater use of inputs.

Further indirect impacts of the adoption of improved crop germplasm are generally evident in the local nonfarm economy as a result of production linkages, such as increased business activity and employment, growth of input supply and service providers, and expansion of traders and processors. Hence, beyond the farmgate, the intensification of wheat production on small and large farms generates additional indirect benefits in that extra farm income stimulates the local nonfarm economy, creates new jobs, and reduces poverty, especially among the landless, those often referred to as the "poorest of the poor" (Dixon, 2007). Furthermore, the transformation and transportation of wheat products from the producer to the consumer can be envisaged as a value chain, often characterized by competitive cooperation among actors along the chain (Kaplinsky and Morris, 2000). Additional indirect effects occur in the nonagricultural sectors as a consequence of consumption linkages, again taking the form of increased commercial activity, employment, and economics growth.

Potential direct and indirect impacts, therefore, need to be taken into account when prioritizing crop improvement research. There is a need to note not only the food security benefits, but also the distribution of benefits among farmers and consumers, the indirect benefits to farmers from diversification, and the benefits to other rural poor through the jobs created in the local nonfarm economy.

Thus, the adoption of improved cultivars is influenced by two important sets of nonfarm factors—the germplasm delivery pathways to the farm and the product-related value chains from the farm to the consumer—which can be visualized as the U-framework. In the early stages of development, impact pathways and value chains can be relatively well-defined single channels. However, they often take the form of webs of interacting agencies and businesses in modernizing economies.

The mapping of impact pathways also allows for the identification of attribution. This is closely linked to the functioning of the innovation network (see above). Generally, impact pathway analysis provides plausible specification of the dominant links and critical roles of the key actors leading to the adoption and better management of improved germplasm and knowledge on farmers' fields. An understanding of these links and roles allows for feedback, and for different actors in the innovation systems (researchers, NGOs, farmers, etc.) to adapt their work to bring about more and better impacts.

Conclusions

Wheat underpins global food security and, therefore, its improvement is critical and has the potential to contribute substantially to the first Millennium Development Goal (MDG) of halving hunger and poverty by 2015, as well as to several other MDGs.

The complex web of partners, who contribute to the process of wheat improvement, from the development of advanced wheat lines by international researchers to the adoption of improved cultivars by farmers, can be considered to be an innovation system.

Generally, there is at least one dominant pathway through the innovation system that carries the major part of the improved germplasm from breeders to farm fields, usually resulting in higher productivity of wheat and improved farm-household livelihoods. This chain represents the first half of the *U impact pathway*. The impact pathway continues, however, with the secondary effects such as farming system diversification that often follows the intensification of wheat. Further indirect impacts of adoption and intensification are generally evident in the local nonfarm economy as a result of production and consumption linkages.

The adoption of improved cultivars is influenced on the demand side by the characteristics of the farm-household system and the wheat marketing or value-adding chains from the farm to the consumer; and on the supply side by the nature and performance of the germplasm/seed delivery pathway from the breeders to the farm. Together the three elements (germplasm delivery pathway, farm-household system characteristics, and the wheat value chain) can be viewed as the U-framework, which determines the rate and magnitude of adoption. In the early stages of agricultural development, germplasm delivery pathways and value chains are barely discernible. Where agriculture is dominated by the public sector, relatively well-defined single channel delivery pathways and value chains are often observed. In marked contrast, in middle-income countries with commercialized agriculture and well-developed institutions, the U-framework often takes the form of webs of interacting agencies and businesses.

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Agricultural R&D Spending at a Critical Crossroads*



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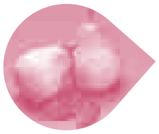
Since 1980 many countries have changed the ways they invest in and organise public agricultural research and development (R&D). Support for public R&D has diminished, especially for near-market, applied, productivity-enhancing research, with funds being diverted to new agendas with environmental and food quality and safety objectives. These changes have important implications for sustaining productivity in developing countries, which in the past have relied on agricultural R&D spillovers from other countries. Some developing countries are becoming more self-reliant and developing their own R&D programs. However, the more disadvantaged countries will struggle to maintain productivity growth in the face of declining applicable spillovers.

Throughout the 20th century, improvements in agricultural productivity have alleviated poverty and starvation and fuelled economic progress. These productivity improvements have been closely linked to investments in agricultural research and development (R&D). However, in the past 25 years many countries have made major changes to the ways they fund and organise public agricultural R&D, and the incentives affecting private R&D. These changes raise questions about the prospects for sustaining productivity growth over the next 25 years and beyond. Early indicators suggest that a global slowdown in farm productivity may have already begun.

Agricultural R&D Trends

In the past, both developing and developed countries have been dependent on technology spillovers from a few of the world's affluent countries, both directly and through the system of International Agricultural Research Centres (IARCs) including the Consultative Group on International Agricultural Research (CGIAR). However, this trend changed towards the end of the 20th century in many countries, with public and private roles shifting. Support for public agricultural R&D slowed, especially for near-market, applied, productivity-enhancing research. In the world's most affluent countries, which traditionally provided the majority of the world's agricultural R&D investments, a slower growing, stagnant, or shrinking pool of public agricultural R&D funding is increasingly being diverted away from the traditional agenda towards environmental objectives, food quality and safety, and other objectives.

These changes mean that many countries (and especially developing countries) may have to become more self-reliant in the development of applicable agricultural technologies. Complete self-reliance will be beyond many countries, especially given recent and ongoing structural changes in science and scientific institutions, in particular the rise of modern biotechnologies and other high-tech agriculture, and the associated role of intellectual property (IP). The largest developing countries (Brazil, China and India) are making the transition; nevertheless, they have



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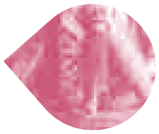

yet to overcome the problem of chronic underinvestment in agricultural R&D, and they have many problems to overcome with respect to the effective management and efficient use of their available resources.

The most disadvantaged countries will continue to rely on the supply of spillovers from other countries and from multinational efforts. However, current international investments in productivity-enhancing agricultural R&D seem too small to fill the vacuum being created by the changes in developed country research agendas.

Who, then, will do the R&D required to generate sustenance for a growing world population when, at least for another century, virtually all the population growth will occur in the poorer parts of the world?

Diverging Research Agendas

During the 1900s, the world's agricultural economy was transformed remarkably, fuelled by agricultural productivity growth, primarily generated by agricultural R&D that was financed and conducted by a small group of developed countries, especially the United States (US), but also France, Germany and Japan.

In an increasingly interdependent world, both developed and developing countries have been dependent on agricultural R&D conducted in the private and public laboratories of these few countries, even though they have not contributed to financing the activity.

However, dietary patterns and other priorities change as incomes increase. As a result, developed country research agendas are shifting. In particular, the past emphasis on simple productivity enhancement and enhancing the production of staple foods is declining in favour of interest in enhancing certain attributes of food (such as increasing demand for processed and so-called functional foods) and food production systems (such as organic farming, humane livestock production systems, localised food sources and 'fair trade' coffee). In contrast, food security concerns are still pervasive among less affluent communities, predominantly in developing countries.

In addition, to growing differences in consumer demand for innovation between developed and developing countries, agricultural R&D agendas may diverge because of differences in producer and processor demands. Farmers in developed countries are demanding high technology inputs that are often not as relevant for subsistence agriculture (such as precision farming technology or other capital-intensive methods).

Agribusiness in developed countries is demanding value-adding processes designed to meet consumer demands, and farm production technologies designed to satisfy evolving demands for farm products with specific attributes such as particular food, feed, energy, medical, or industrial applications.

As developed country agricultural R&D programs respond to these changing patterns of demand for innovations, the emphasis of the science is being skewed in ways that could undermine the international spillovers that have traditionally contributed significantly to gains in food production throughout developing countries of the world. These spillovers are not generally well understood and their importance is under-appreciated.

Other aspects of agricultural science policy, and the context in which it is conducted, are changing as well. In particular, the rise of modern biotechnology and enhanced intellectual property rights (IPRs) regimes mean that the types of technologies that were once freely available will be more difficult to access in the future.

Moreover, the new technologies may not be as portable as in the past. Biotech companies are mostly located in developed countries, particularly in the US, and tend to emphasise technologies that are locally applicable.

These and other factors limit incentives for companies to develop technologies for less-developed countries. Hence, some fear less-developed countries may become technological orphans, abandoned by their former private- and public-sector benefactors in developed countries.

New Pressures for Self-Reliance

International spillovers of public agricultural R&D results are extremely important as they have profound implications for the distribution of R&D benefits between consumers and producers, and thus among countries (Alston 2002). They have also contributed to a global underinvestment in agricultural R&D, which the existing public policies have only partly succeeded in correcting. The stakes are high because the benefits from agricultural technology spillovers are worth many times more than the investments that give rise to them.

The world's least affluent countries have depended on spillovers of technologies from industrialised countries (especially from the US, but also the United Kingdom, France and others) both individually and through their collective action via the CGIAR.

Until recently, much of the successful innovative effort in most developing countries was applied at the very last stage of the process, selecting and adapting varieties for local conditions using breeding lines and other materials developed elsewhere. Only a few larger countries, such as Brazil, China and India, were able to achieve much by themselves at the more upstream stages of the research and innovation process, even for improved crop technologies for which conventional breeding methods are widely applied.

Until recently, that strategy of conducting adaptive research and relying on spillovers for basic material was reasonable, given an abundant and freely accessible supply of suitable materials; at least for the main temperate-zone food crops.

Changes in the emphasis of developed country agricultural R&D, combined with new IP rules and practices in conjunction with an increased use of modern biotechnology methods, have already begun to spell a decline in the public pool of new varieties. In addition, the other main source of varietal materials, the CGIAR, has changed its emphasis and is scaling back its role of providing finished material or advanced breeding lines.

The reduction in spillovers from these traditional sources will mean that less-developed countries will have to find new ways of meeting their demands for new varieties.

Pervasive Underinvestment

Although investment in agricultural R&D has high returns and has played a major role in helping to provide food for large and expanding populations, support for this form of R&D is declining. Underfunding of agricultural R&D is pervasive, especially in developing counties. This trend is alarming given:

- the continuing and substantive growth of populations, especially in developing countries
- an increasingly scarce and deteriorating natural resource base
- the pervasive pockets of hunger and poverty that persist in developing countries, in many cases despite impressive national average productivity increases
- the growing divergence between developed country research agendas and the priorities of developing countries.

The problem of underfunding may worsen, especially for agricultural R&D that is related to the production of food staples in less-developed countries, as evidenced by the recent funding trends.

Public Research Investments

Worldwide public investment in agricultural R&D increased by 51% in inflation-adjusted terms between 1981 and 2000 from an estimated $15.2 billion to $23 billion in 2000 international dollars. During the 1990s, for the first time, developing countries as a group provided more of the world's public agricultural R&D than developed countries did (Figure 1).

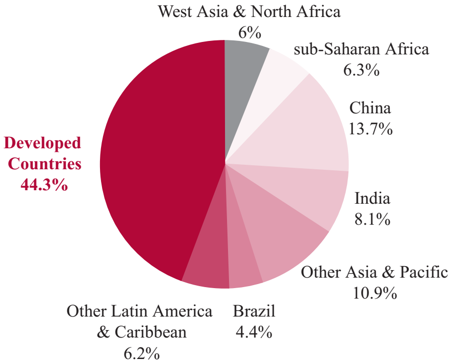

Figure 1: Global public investment in agricultural R&D: 2000.[a]

[a] Data is reported in international dollars based on purchasing power parity conversions of local currency units in 2000 prices.

Source: Pardey et al. 2006a

The Asia and Pacific region has continued to gain ground, accounting for an ever-larger share of the developing country total since 1981. In 2000, just two countries from this region, China and India, accounted for 39.1% of developing country expenditure on agricultural R&D; a substantial increase from their 22.9% combined share in 1981. In stark contrast, sub-Saharan Africa continued to lose market share, falling from a 17.3 to 11.4% share of the developing country R&D investment total between 1981 and 2000 (Pardey et al. 2006a).

Paralleling spending patterns for all the sciences, agricultural R&D has become increasingly concentrated in a handful of countries. Just four countries (the US, Japan, France and Germany) accounted for 66% of the public R&D conducted by developed countries in 2000; about the same as two decades before. Similarly, just five developing countries (China, India, Brazil, Thailand and South Africa) undertook 53.3% of the developing countries' public agricultural R&D in 2000, up from 40% in 1981. Meanwhile, in 2000, a total of 80 countries with a combined population of approximately 625 million people conducted only 6.3% of total agricultural R&D (Pardey et al. 2006a).

The patterns of spending growth are uneven. Certainly, the more recent rates of increase in inflation-adjusted spending for all developing regions of the world failed to match the rapid ramping up of public agricultural R&D spending that Pardey and Beintema (2001) reported for the 1970s.

The growth in spending for the Asia and Pacific region as a whole rebounded in the late 1990s from the slower growth rates observed for the 1980s. This was especially so in China and India during the 1996 to 2000 period, in both instances reflecting government policies to revitalise public R&D and improve its commercialisation prospects, including linkages with the private sector.

Spending growth throughout the Latin American region as a whole was more robust during the 1990s than the 1980s; although the recovery was more fragile and less certain for some countries in the region (such as Brazil, where spending contracted at the close of the 1990s).

Overall investments in agricultural R&D in sub-Saharan Africa failed to grow by more than 1% per annum during the 1990s; the continuation of a longer-term slowdown (Beintema & Stads 2004). Even more concerning is the fact that approximately 50% of the 27 African countries for which national total estimates are available, spent less on agricultural R&D in 2000 than in 1991 (Beintema & Stads 2004).

A notable feature of the trends was the contraction in support for public agricultural R&D among developed countries. While spending in the US increased in the latter half of the 1990s, public R&D was massively reduced in Japan (and also, to a lesser degree, in several European countries) towards the end of the 1990s, leading to a decline in developed country spending as a whole for the decade.

The more recent data reinforce the longer-term trends observed earlier. Namely a fairly widespread scaling back, or at best a slowing down of support for publicly performed agricultural R&D among developed countries is occurring. In part, this points to a shifting emphasis from public to privately performed agricultural R&D, but also to a shift in government spending priorities.

Inevitably, this will affect productivity prospects in agriculture for the countries in question. Pardey et al. (2006b) suggest a more subtle and arguably more important consequence is that a slowdown or cutback in developed country spending will curtail the future spillover of ideas and new technologies from developed and developing countries.

Developed-developing country linkages will be even more attenuated as the funding trends proceed in parallel with other policy and market developments. These include strengthening IPRs and biosafety regulations, and a reorientation of developed country R&D agendas away from productivity gains in food staples towards concerns for the environmental effects of agriculture and food quality, as well as the medical, energy, and industrial applications of agricultural commodities.

With developed countries as a group still accounting for 44% of public agricultural R&D worldwide (and nearly 80% of all science spending) the consequences of a continuation of these funding, policy, and market trends is likely to be particularly pronounced in terms of the productivity-enhancing effects on food staples.

In addition to these broad trends, other aspects of agricultural R&D funding that have important practical consequences are also of concern. For example, undue variability in R&D funding continues to be problematic for many developing country research agencies. This is especially troubling for agricultural R&D given the long gestation period for new crop varieties and livestock breeds, and the desirability of long-term employment assurances for scientists and other staff (Pardey et al. 2006b).

Variability encourages an over-emphasis on short-term projects or on projects with short lags between investment and outcomes, and adoption. It also discourages specialisation of scientists and other resources in areas of work where sustained funding may be uncertain, even when these areas have high pay-off potentials.

Public Agricultural R&D Intensities

Turning now from absolute to relative measures of R&D investments, developed countries as a group spent $2.36 on public agricultural R&D for every $100 of agricultural output in 2000; a sizable increase over the $1.41 spent per $100 of output two decades earlier, but slightly down from the 1991 estimate of $2.38 (Figure 2). This longer-term rise in R&D intensity in developed countries starkly contrasts with the group of developing countries where there was no measurable growth in the intensity of agricultural R&D (i.e. agricultural R&D spending expressed as a percentage of agricultural gross domestic product). In 2000, developing countries spent just $0.53 on agricultural R&D for every $100 of agricultural output.

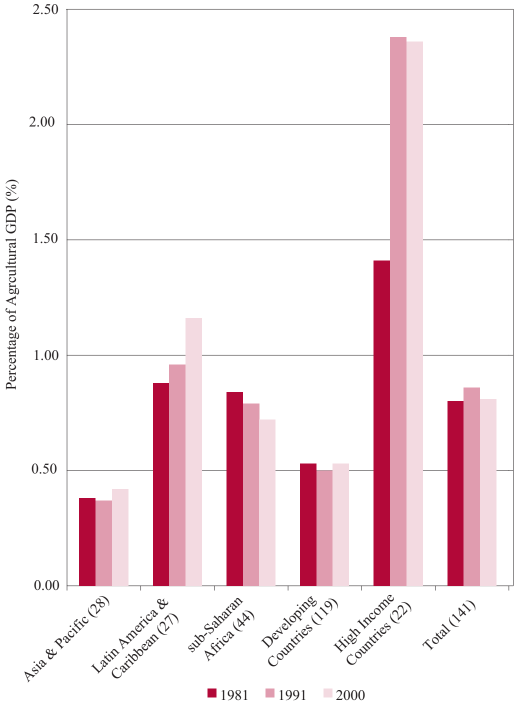

Figure 2: Regional comparisons of public agricultural R&D intensities: 1981–2000.

Source: Pardey et al. 2006a

At first glance the rise in developed country intensity ratios and the stagnating R&D intensities for developing countries appears to misrepresent the trends in spending, which showed that the growth in investments in agricultural R&D in developing countries significantly outpaced the corresponding growth in investments in agricultural R&D in developed countries (i.e. 3.13 versus 2.11% per annum from 1981–2000). Delving deeper, agricultural output grew much faster in aggregate for developing versus developed countries over the previous several decades, so that the faster growth in aggregate agricultural R&D spending among developing countries had, nonetheless, barely kept pace with the corresponding growth in output. In addition, more than half of the developed countries, for which data were available, had higher R&D intensity ratios in 2000 than 1981. The majority spent in excess of $2.50 on public agricultural R&D for every $100 of agricultural gross domestic product. Only 10 of the 26 countries in sub-Saharan Africa in the sample had higher intensity ratios in 2000 than in 1981, while most countries in the Asian and Latin American sample increased their intensity ratios from 1981 to 2000 (9 out 11 Asian countries and 8 out of 11 Latin American countries).

Other research intensity ratios are also revealing. Developed countries spent $692 per agricultural worker in 2000; more than double the corresponding 1981 ratio while developing countries spent just $10 per agricultural worker in 2000, an increase of less than 50% over the 1981 figure. These developed-developing country differences are, perhaps, not too surprising. A much smaller share of the developed country workforce was employed in agriculture, and the absolute number of agricultural workers declined more rapidly in developed countries than it did in the developing ones.

While only some segments of society are directly involved in agriculture as producers, everyone consumes agricultural outputs, therefore agricultural R&D spending per capita is instructive. These new data signalled a break with earlier trends. For developed countries, spending per capita rose substantially from 1981 to 1991 (a continuation of earlier trends documented by Pardey & Beintema 2001), but declined thereafter so that spending per capita in 2000 had slipped well below 1991 levels. This developed country reversal was driven mainly by developments in Japan, although only half the developed countries continued to increase their per capita spending on agricultural R&D throughout the 1990s.

Per capita spending rates were much lower among developing compared with developed countries; typically less than $3 per capita for developing countries (especially those in Africa) whereas 59% of the developed countries invested more than $10 per capita in 2000. Nonetheless, and in contrast to the group of developed countries, spending per capita for the group of developing countries continued to rise from $2.09 per capita in 1981 to $2.72 in 2000. The outliers to this general trend are sub-Saharan Africa, where agricultural R&D spending per capita has continued to decline since 1981, and Latin America, where spending per capita declined from $5.43 in 1981 to $4.94 in 1991 and $4.96 in 2000.

Private Agricultural R&D Investment

In agriculture, in particular, it is difficult for individuals to fully appropriate the returns from their R&D investments, and it is widely held that some government action is warranted to ensure an adequate investment in R&D (Pardey et al. 2006b). The private sector has continued to emphasise inventions that are amenable to various IP protection options such as patents, and more recently, plant breeders' rights and other forms of IP protection.

Private investments in agricultural R&D, similar to investments in all forms of R&D, are motivated and sustained by the returns to innovation reaped from the investment.

IP policies and practices are but one dimension of the incentive to innovate. Potential market size and the cost of servicing the market, which in turn are dependent on the state of communication and transportation infrastructure, farm structure and size, and farm income, are important dimensions as well. So too is the pattern of food consumption. As incomes rise, a larger share of food expenditure goes to food processing, convenience and other attributes of food, areas where significant shares of private agricultural R&D effort are directed.

The private sector has a large presence in agricultural R&D, but with dramatic differences between developed and developing countries and among countries. In 2000, the global total spending on agricultural R&D (including pre-, on- and post-farm oriented R&D) was $36.5 billion. Approximately 37% was conducted by private firms and the remaining 63% by public agencies. Notably, nearly 94% of that private R&D was performed in developed counties, where some 55% of the agricultural R&D was private (Table 1).

In developing countries, only 6% of the agricultural R&D was private, and there were large disparities in the private share among regions of the developing world. In the Asia and Pacific region, around 8% of the agricultural R&D was private, compared with only 2% of the R&D throughout sub-Saharan Africa.

The majority of private R&D in sub-Saharan Africa was oriented to crop-improvement research, often (but not always) dealing with export crops such as cotton in Zambia and Madagascar and sugarcane in Sudan and Uganda. Almost two thirds of the private R&D performed throughout the whole region was carried out in South Africa.

The private share of agricultural R&D spending in Organisation for Economic Co-operation and Development (OECD) countries grew steadily from nearly 44% in 1981 to over 55% in 2000 (Table 1). These increasing private shares reflected increasing industry R&D by the farm-input supply and, especially, the food processing sectors.

Table 1: Private sector share of total agricultural R&D: 1981–2000.

Region	1981 (%)	1991 (%)	2000 (%)
Australia	5.9	20.2	23.5
Japan	36.6	48.4	58.6
United States	50.1	54.3	54.6
Other (19)	45.7	48.5	56.9
Total	43.9	49.6	55.2

Source: Compiled by authors from data reported at www.asti.cgiar.org

Around the general trend was much country-specific variation. In the US the private share inched up from 50.1% (compared with an OECD average of 43.9%) in 1981 to 54.3% by 1991, and changed little thereafter. According to these data, Japan conducted slightly more of its agricultural R&D in the private sector than the US. The private share of Australian agricultural R&D has also grown from a small base of 5.9% in 1981 to 20.2% in 1991, then more slowly during the next decade to 23.5% of the total in 2000.

Policy Implications

Agricultural R&D is at a crossroads. The close of the 20th century marked changes in policy contexts, fundamental shifts in the scientific basis for agricultural R&D, and shifting funding patterns for agricultural R&D in developed countries. These changes imply a requirement for both rethinking of national policies and reconsidering multinational approaches to determine the types of activities to conduct through the CGIAR and similar institutions and how these activities should be organised and financed.

Even though there is no evidence to suggest that the world can afford to reduce its rate of investment in agricultural R&D and there is every indication that more should be invested, it cannot be assumed that developed countries will play the same role as in the past.

In particular, countries that in the past relied on technological spillovers may no longer have that luxury available to them in the same ways or to the same extent. This change can be seen as involving three elements:

1. The types of technologies being developed in the developed countries may no longer be as readily applicable to less-developed countries as they were in the past.

2. Those technologies that are applicable may not be as readily accessible because of IP protection of privately owned technologies.
3. Those technologies that are applicable and available are likely to require more substantial local development and adaptation, calling for more sophisticated and more extensive forms of scientific R&D than in the past.

In short, different approaches may have to be devised to make it possible for countries to achieve equivalent access and tap into technological potential generated by other countries, and in many instances countries may have to extend their own agricultural R&D efforts farther upstream, to more fundamental areas of the science.

Conclusion

The balance of global agricultural R&D investments is shifting in ways that will have important long-term consequences, especially for the world's least affluent countries. The primary reason is changes in supply and demand for agricultural technologies in developed countries, which have been the main producers of agricultural technologies.

These countries seem unlikely to provide the quantities of productivity-enhancing technologies, suitable for adaptation and adoption in food deficit countries, that they did in the past. This trend has been compounded by a scaling back of developed country support for the international agricultural R&D system, which has already diverted its own attention away from finished productivity-enhancing technologies, especially for staple food crops.

A shift in R&D agendas is forcing a rethinking of some national and multinational policies. National Governments can take some initiatives in national agricultural R&D policy, such as: enhancing IP and tailoring the institutional and policy details of IPRs to best fit local circumstances; increasing the total amount of government funding for their national agricultural R&D systems; introducing institutional arrangements and incentives for private and joint public-private funding; and improving the processes by which agricultural R&D resources are administered and allocated.

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Note

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Summary of evaluation questionnaire for the International Symposium on Increasing Wheat Yield Potential

(Petr Kosina, Impacts Targets and Assessments Unit, CIMMYT)

63 questionnaires received (total number of participants = 148)

Information about respondents (of 63 received questionnaires):

- 27 senior scientists - 14 scientists - 9 Managers/directors - 7 students - 4 postdocs - 2 other	- 34 from developed countries - 26 from developing countries - 3 unidentified	- 24 were participating for the first time in CIMMYT event - 39 had already participated in some other CIMMYT event

Worthiness of symposium:

- Respondents were very satisfied with overall symposium (4.5 on 5 point scale).
- Respondents were satisfied with presented topics and their relevance (4.27 on 5 point scale).
- Respondents were satisfied with usefulness of the information to their research (4.26 on 5 point scale).
- Respondents were satisfied with the amount of time to network and share ideas with other participants (4.11 on 5 point scale).
- Respondents expressed their satisfaction with motivational experience from the symposium (4.29 on 5 point scale).

Effectiveness and length:

- Majority of respondents agreed that such a symposium should be repeated regularly in similar form as it was organized. (4.4 on 5 point scale).
- Vast majority (45 out of 63) recommended that symposium should be repeated every 3-5 years.
- Vast majority (58 out of 63) considered time allocated to the symposium (5 days) as appropriate.

Summary of written comments:

What was the most beneficial aspect of the symposium to you?

Clearly the most often mentioned beneficial aspect of the Wheat Yield Potential Symposium was networking—interactions with participants from other countries (especially interaction between scientists from NARS and ARIs)—to discuss the challenges and new trends, information exchange and knowledge sharing.

Somewhat contradictory comments were received in relation to the spectrum of topics that were covered in presentations during symposium. Although some participants appreciated the relevancy of the variety of topics that were presented, others asked for a narrower focus for the symposium.

Another often mentioned beneficial aspect of the symposium was learning about CIMMYT's research and role in global context, however, a few respondents would have preferred more non-CIMMYT speakers.

Other valued aspects of symposium included mainly the topics of physiology, molecular biology, future strategies of increasing yield potential, the field day at CIMMYT's research station, and brainstorming.

What other topics or themes are of interest to you for the next similar symposium?

Most often mentioned themes to be added or to have more time dedicated for the next or similar symposia were **breeding methodologies and strategies**; **molecular techniques** (especially MAS, QTL for traits of interest) and their practical implication (phenotyping), and **pathological aspects** (durable resistance)

Several respondents also asked for more active participation from NARS, and better representation of the some regions since certain countries were not represented. Also missing were representatives of universities. "There should be one day oral presentations solely from NARS scientists. …."

In relation to the field day at the CIMMYT experimental station, respondents asked that more time be given in field to follow up on special interests, and that less time be spent on presentations. More time should be allotted for 'interactions' related to particular plots.

Other topics that were mentioned several times (to be included or expanded in the future symposiums) included statistics and bioinformatics, quality (why domestic markets get the inferior quality product?), and abiotic stresses other than drought.

The following are topics mentioned by individual respondents: (i) the role of future researchers, where are we heading?; (ii) nutrient physiology; (iii) seed multiplication and trade diversification of wheat products; (iv) wheat quality relative to physiological aspects and genetics.

Additional comments

Many respondents expressed their appreciation for a job well done by the symposium organizers (friendly and helpful support staff).

The symposium was characterized as very stimulating.

Several respondents mentioned, that ‘the day program seemed to be overfilled.’ While they considered afternoon brainstorming very interesting (although could be better structuralized), they said that it might be more efficient if participants were not fatigued by the large number of presentations earlier in the day.

Overlap and redundancy in some presentations was sometimes observed.

Some thought that some of invited speakers should come with new ideas and challenges rather than reviewing other scientists’ work

Prior to the meeting, the program for the final day was not clear about participants /objectives for those sessions.

Logistics:

- The poster session could have been somewhat more organized.
- The afternoon of the field day could have been better organized.
- Would be useful to have names of organizations on name tags.
- Hard copy proceedings will be needed for NARS. Ensure that there are papers/pieces in the proceedings for the NARS posters.

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