# International Wheat Improvement: Highlights from an Expert Symposium

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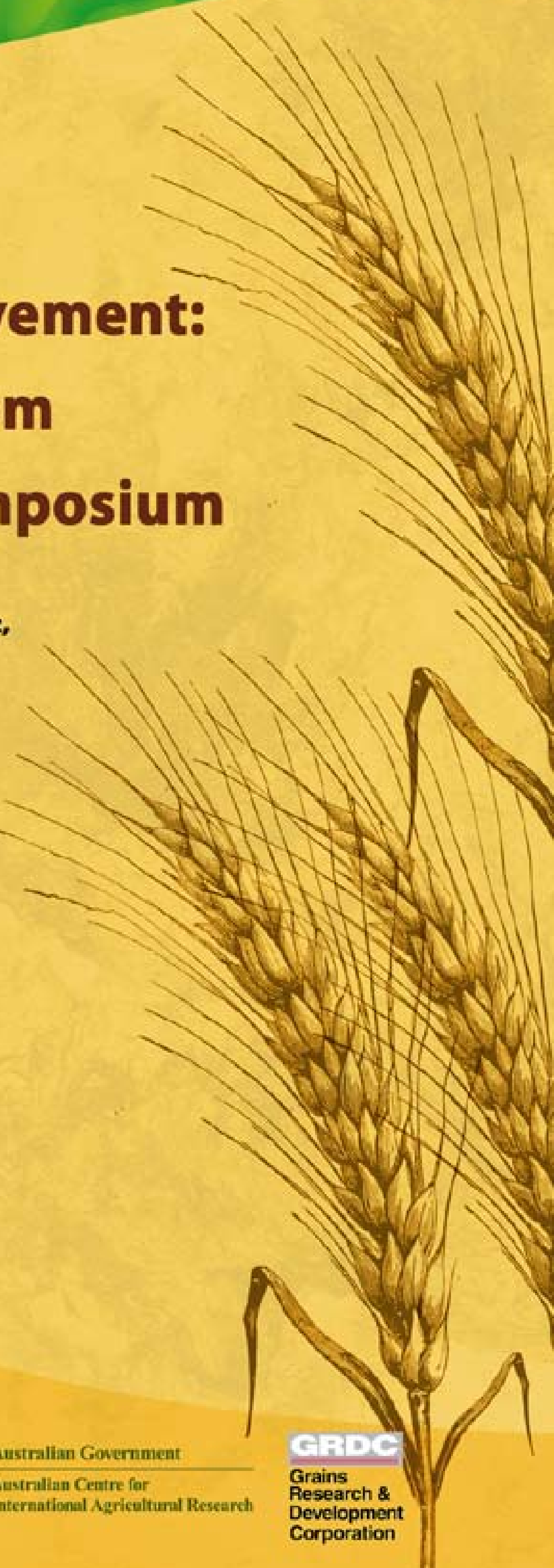

CIMMYT

Australian Government
Australian Centre for International Agricultural Research

GRDC
Grains Research & Development Corporation

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Wheat is grown on 217 million hectares worldwide, accounting for some 620 million tons of grain and providing one-fifth of the world's total calorific input. In regions like North Africa, Turkey, and Central Asia, wheat provides fully half of total dietary calories. Half the world's wheat area is found in developing countries, where steady increases in productivity since the Green Revolution, associated with improved yields, resistance to diseases, adaptation to abiotic stresses, and better agronomic practices, are now under serous threat. Challenges include increased demand, scarcity of water resources, unpredictable climates, increased urbanization and loss of quality farmland, and decreased public investments in agriculture. To meet the rising demand for wheat in a sustainable way, farmers need a new generation of improved cultivars, along with resource-conserving practices to grow them.

In March 2006, with support from the Australian Centre for International Agricultural Research (ACIAR), CIMMYT brought together 160 scientists from over 30 wheat-producing countries to discuss how to increase wheat production sustainably. Their presentations and discussions are being assembled in the proceedings *International Symposium on Wheat Yield Potential: Challenges to International Wheat Breeding*, to be published by CIMMYT in March 2008. The volume will include articles from the symposium already published in 2007 in special issues of *Euphytica* (volume 157:3) and the *Journal of Agricultural Science* (volume 145:1-3), as well as other papers from the meetings:

- Reports of the workshop “Stakeholder priorities for internationally-coordinated wheat research” involving representatives of major wheat producing countries on all continents whose remit was to develop a list of priorities for future wheat research that could best be tackled in a globally-coordinated fashion, and outlines of activities that would serve as templates for future project development for selected priorities.
- The summary of field day presentations by groups of collaborating scientists in attendance, illustrating the continuum between national, regional, and international-center-based research activities.
- 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. Collectively these countries account for over 100 million hectares of wheat and around 90% of the wheat production in the developing world. The data were also used to prepare a general summary of the constraints to productivity and research across the above-mentioned regions.

## Summary of the Plenary Presentation

The symposium opened with the address by Nobel Laureate Dr. **Norman Borlaug**: "Sixty-two years of fighting hunger: Personal recollections," describing the evolution of international wheat breeding, including the use of "shuttle breeding" to overcome photoperiod sensitivity and thereby develop broadly adapted germplasm. His talk also touched on the emergence of the virulent new stem rust race Ug99 from eastern Africa and the evolution of internationally coordinated research on global public goods in agriculture, leading to the formation of the Consultative Group of International Agricultural Research (CGIAR). He specifically addressed high-yielding 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

In his article "Application of new knowledge, technologies, and strategies to wheat improvement," **Sorrels** highlights the complexity of the genomes of graminaceous crops and the fact that they are rapidly evolving and heterogeneous, even within species. He 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**. 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. The genetic potential of re-synthesized hexaploid germplasm was investigated by Ogbonnaya et al., who found that synthetic-derived lines yielded 8-30% higher than the best local check in multi-site trials across diverse regions of Australia. **Kishii et al**. reiterate the idea that numerous 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," advocates careful assessment of new approaches, based on scale of operation, with low-cost investments being more universally accessible.

## Value of Internationally Coordinated Breeding Efforts

**Rajaram and Braun** review efforts over the last 50 years to increase yield potential while improving adaptation to biotic and abiotic stresses. Percent gains have been similar in irrigated and rainfed areas in absolute terms, but productivity has increased considerably more in irrigated areas. The authors underscore the need for germplasm that tolerates abiotic stresses without sacrificing yield in favorable years, and the value of introducing new genetic diversity.

In "High yielding spring bread wheat germplasm for global irrigated and rainfed production systems," **Singh et al**. report that grain yields of the best new entries were 10% higher than those of local checks in international yield trials. While not all genotypes respond as well across sites, analysis of genotype x environment interaction provides opportunities to select for stable genotypes. As outlined by **Ortiz et al**., 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 diseases, while incorporating as much genetic diversity as possible into entries for international nurseries. The article also debates the relative roles of international centers like CIMMYT versus national agricultural research systems in developing countries: should the centers invest more in strategic germplasm enhancement, with adaptive breeding being conducted by national systems?

An analysis of 40 years of international spring bread wheat trial data by **Trethowan and Crossa** confirms the relevance of shuttle breeding in Mexico and describes how integrating the resulting information with international trial data benefits CIMMYT and partners. **Ammar et al**. highlight the successes of international durum wheat yield trials over 22 years, based both on shuttle breeding in Mexico and work with a global network of partners.

**Chapman et al**. and **Ortiz-Ferrara et al**. assess the advantages of incorporating key genes, such as those for plant height, in wheat breeding lines, and of participatory research and client-oriented plant breeding. In "Relationships between height and yield in near-isogenic spring wheats that contrast for major reduced height genes," Chapman et al. show how the environment influences 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 nearly 10% yield gain for lines possessing such genes. Genotype x environment interaction—especially of the cross-over type—was identified by symposium participants as impeding wheat improvement, especially for quantitative traits. **Eagles et al**. suggested that molecular and statistical technologies can be used to assist breeding for polygenic traits such as yield. Ortiz-Ferrara et al. describe how, through participatory approaches, several farmer-preferred technologies have been identified for adverse conditions in eastern India and Nepal, increasing grain harvests of resource-poor farmers by 15-70%.

Advances in wheat improvement must also consider end-uses. Negative correlations between grain yield, grain protein concentration, and end-use are described by **De Pauw et al**. in "Shifting undesirable correlations," concluding that such correlations can be remedied by developing plants that efficiently produce and partition carbohydrates to grain yield and have improved nitrogen- and water-use efficiency, through simultaneous selection for quantitative and quality traits aided by use of DNA markers. Echoing previous statements on the value of wild species, **Peña** remarks that introducing protein-enhancing genes from *Triticum dicoccoides* can increase grain protein content while improving both grain yield and quality.

Addressing a subject worthy of a symposium in its own right, **Duveiller et al**. present strategies aimed at minimizing or controlling yield losses from major diseases and pests in intensive irrigated wheat systems. Options 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 use of fungicides. Their article, "The challenges of maintaining wheat productivity: pests, diseases, and potential epidemics," also advises about the risk of changes in disease spectra as a result of climate change.

## Regional Challenges

Several papers address wheat improvement in major grain baskets around the world. **Joshi et al**. point out that India "…faces a critical challenge in maintaining food security in the face of its growing population," and that wheat breeders there should focus on heat stress, water scarcity, the threat of new virulence in major diseases, the adoption of resource-conserving practices, and grain quality. Challenges to wheat production in South Asia in terms of biotic and abiotic stresses are also described by **Chatrath et al**., who point to stagnating wheat yields and the declining productivity of rice-wheat systems due to intensive tillage, the burning of residues, and the depletion of soil organic carbon. Along similar lines, **Gupta and Sayre** analyze the benefits of conservation agriculture in the region.

Identifying wheat genotypes that provide high and stable grain yields is of particular relevance for poor farmers. **Sharma et al**. report results for the Eastern Gangetic Plains Yield Trials, 1999-2005. Lines with improved yield stability and disease resistance were identified and released, which underlines the relevance of regional wheat breeding programs. Similarly, **Zhou et al**. evaluated grain yield gains in Southern China's winter wheat areas, using leading cultivars released from 1949 to 2000 and showing increases of 0.31% and 0.74% per year in the two regions studied. Challenges for this setting include improving yield and disease resistance and developing cultivars for reduced-tillage rice-wheat systems.

**Morgounov and Trethowan** reviewed recent work in the short-season, high-latitude areas of northern Kazakhstan and Siberia, where yields are limited by lack of moisture in the dry years and by leaf rust in wetter years. They suggest three main approaches to address this: improved agronomic practices, better adapted germplasm, and policy interventions. In a similar vein, **Scheeren et al**. highlight the importance of agronomic practices, improved varieties, and management policies to increase productivity in Brazil's wheat lands. **Pardey et al**. (2006) remark that some developing countries are becoming more self-reliant in research and development programs, but that disadvantaged countries will struggle to maintain productivity growth in the face of declining spillovers.

In a survey of breeders from 19 countries representing 90% of all wheat grown the developing world, **Kosina et al**. found that the most significant wheat production constraints are heat and water stress, weeds, and diseases, and the most desired outputs from international centers include germplasm development and exchange, assistance in capacity building, and knowledge sharing.

## Progress in Understanding the Physiological Bases of Yield

Two papers—**Fischer** and **Foulkes et al**.—review recent work on the physiological bases of wheat yield increases, with the latter focusing more on winter wheat. Data from the last 10 years in northwestern Mexico indicate that yield increases in CIMMYT spring wheat have slowed to around 0.5% per year, although physiological understanding has advanced. New research reinforces the importance of spike dry weight ($g/m^2$) at anthesis and suggests lengthening the spike growth period by manipulating photoperiod sensitivity, a subject addressed in depth by **Miralles and Slafer**. Despite producing more kernels/$m^2$, the latest wheat cultivars still appear to be largely sink-limited during grain filling. Evidence from wheat and other cereals indicates the importance of increased photosynthetic activity before and during flowering (**Reynolds et al**.). 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 bases of genotype x year interactions, which are specifically addressed in **Vargas et al**. Path analysis for genotype x environment interactions using structural equation modeling enables a number of response variables to be modeled 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 associated with biomass, in contrast to partitioning alone. In winter wheat, recent biomass progress was related to pre-anthesis radiation-use efficiency and water-soluble carbohydrate content of stems at anthesis. The authors also highlight the value of introducing alien genes and, finally, list traits to raise winter wheat yield potential in northwestern Europe.

Miralles and Slafer and Reynolds et al. consider the issue of sink and source limitations in some detail. The former sketch out evidence that further increases in grain number/$m^2$ may be achieved by fine-tuning pre-anthesis developmental patterns to increase the rapid spike growth period without altering flowering time. They recommend

QTL analysis to identify genetic markers for which they and their colleagues have already provided a substantial background of phenotypic data. Reynolds et al. look at both source and sink limitations in populations of random sister lines to establish a more definitive link with productivity. The associated traits formed three main groups relating to phenological pattern of the crop, assimilation capacity until shortly after anthesis, and partitioning of assimilates to reproductive structures shortly after anthesis.

**Parry et al**. considered the issue of increasing assimilation capacity at the cellular level by overcoming C3 limitations of Rubisco and by increasing the concentrations of substrates, $CO_2$, and Ribulose biphosphate (RuBP) at the active site of Rubisco, such as naturally occurs in C4 plants.

Another issue addressed at the symposium was the use of physiological selection criteria for high-yielding environments. **Condon et al**. summarized results indicating the potential of using physiological traits associated with stomatal aperture—such as canopy temperature, leaf conductance, and carbon isotope discrimination—as a complement for visual selection in early breeding generations, to break barriers to bread wheat yield potential. Similar results are reported by **van Ginkel et al**., who focused on use of canopy temperature depression during the selection of segregating generations to positively skew gene frequency for yield and adaptation. The economic assessment presented by **Brennan et al**. of the use of physiological selection for stomatal aperture-related traits in CIMMYT wheat breeding lends strong support to the potential value of that approach; as just one example, it facilitates discarding physiologically substandard lines prior to extensive yield testing.

## Agronomic and Environmental Strategies for Raising and Sustaining Productivity

CIMMYT and other CGIAR research groups have made major contributions to agricultural development, but experts in geographical information systems (GIS) **Hodson and White** postulate that the continued ability to do so will depend on an increased ability to collect, analyze, and assimilate large amounts of spatially-oriented agronomic and climatic data. 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, and describe several examples of such applications to help predict the effects of climate change and classify production environments by combining biophysical and socioeconomic criteria. According to **Dixon et al**., these tools and techniques are equally applicable for developing long-term cropping systems strategies to maximize the productivity of agro-ecosystems through appropriate conservation agricultural practices that incorporate local microeconomic factors.

**Hobbs** describes conservation agriculture as the combination of minimal soil disturbance, permanent soil cover, and rotations to reduce wind and water erosion, increase water infiltration, and save farmers money and time. He also outlines the physical, biological, chemical, and environmental benefits of zero-tillage, currently practiced on nearly 100 million hectares in the world, and explains the importance of developing suitable equipment to enable farmers to adopt this green technology. **Ransom et al**. describe a similar no-till, crop rotation system for dryer regions of North Dakota that results in significant yield increases and conserves soil productivity, and conclude that identifying or developing crop management practices to exploit positive genotype x management interactions is needed.

According to **Gupta and Sayre**, resource-conserving practices such as zero-tillage and residue retention are becoming popular in the rice-wheat systems of the Indo-Gangetic Plains of South Asia, leading to improved profits and yields and impacting on various environmental factors. In 2005-2006 season, nearly 3 million hectares of wheat were sown this way, and the benefits have encouraged researchers and farmers to explore practices such as laser levelling, cropping diversification, and even zero-tilled, direct seeded rice.

Based on long-term trials in the Yaqui Valley in northwestern Mexico, **Sayre et al**. present convincing data concerning the feasibility for permanent, raised beds and conservation agriculture technologies to dramatically reduce tillage, save water and costs, manage retained residues on the soil surface, and diversify crop rotations in intensive, irrigated wheat systems, resulting in the same physical, biological, and chemical benefits outlined in the Hobbs paper.

Two papers, **Ortiz-Monasterio** and **Raun** and **Girma et al**. look at ways to improve nitrogen-use efficiency (NUE) in wheat, thereby reducing farmers' costs and negative environmental effects from nitrification and run-off into waterways. The first paper draws on data from the Yaqui Valley, where NUE has been estimated at 0.31, and describes tests with infrared sensors to help better target fertilizer for wheat on large commercial farms, showing potential savings of 69 kg N/ha without a yield penalty (a saving of US$ 62/ha). Girma et al. used a similar approach—the sensor, the normalized difference vegetation index (NVDI) calibration stamp, N-rich strips for comparison, and ramped calibration strips—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.

**Dixon et al**. draw on a wide spectrum of recent literature to look 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 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 highlighted reasons for optimism about improving the impact of wheat breeding, via new technologies, while underscoring the considerable challenges faced by agricultural researchers. Current slow, though steady, increases in wheat yield potential are clearly insufficient to meet predicted global demand. Research of the last two decades, however, has made progress in fields, which, if brought to a common platform, could substantially increase farm-level productivity. These include our understanding of the physiological bases of yield in wheat, rapid development of molecular markers for traits associated with improved yield, a new generation of statistical tools that permit dissection of genotype x environment interaction into its genetic and physiological components, and a rapidly-growing body of practical knowledge to implement conservation agriculture practices that could 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 the application of molecular markers in breeding, along with its well-developed network of scientists in national programs and advanced research laboratories around the world, is strategically positioned as a focal point for these and related efforts to raise the productivity of wheat farming systems in developing countries.

**The proceedings "International Symposium on Wheat Yield Potential: Challenges to International Wheat Breeding," will be published by CIMMYT in March 2008 on the center's website and as a limited number of printed copies. So that we can notify you when publication occurs, please indicate your interest by sending a message to administrative assistant, Liliana Villaseñor (l.villasenor@cgiar.org) with "Wheat Proceedings" in the heading and your full contact information, or pass a written message to one of the representatives of CIMMYT attending the CGIAR annual general meeting.**

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