Journal of Wheat Research 1(1&2) : 13-18 (2007)

Increasing genetic yield and mitigating effects of key biotic and abiotic constraints to wheat production in India through international wheat resources and partnerships

RAVI P SINGH

International Maize and Wheat Improvement Center (CIMMYT), Apdo. Postal 6-641, 06600, Mexico D.F., Mexico

ABSTRACT

The surplus wheat production in India and the world in the 1990s have eroded in recent years due to stagnating productivity and increasing demands. Production must increase at least 2% annually until 2020 to meet future demands. Breeding wheat cultivars that have increased grain yield potential, enhanced water-use efficiency, heat tolerance, end-use quality, and durable resistance to important diseases and pest could contribute to meet about half of future demand. The remaining half must come through better agronomic and soil management practices and incentive policies. International partnerships allow the most efficient use of genetic diversity present in improved wheat germplasm and genetic resources necessary to continue making genetic progress especially for resistance and tolerance to abiotic and biotic stresses. Breeding and testing schemes that would accelerate the recovery of rare superior progenies should be explored and applied. The "International Wheat Improvement Network" operated by CIMMYT in partnership with many wheat improvement programs develops, distributes and tests improved wheat materials globally. New triple rust resistant wheat germplasm from CIMMYT has shown 15% higher yield potential over current popular cultivar in the Northwestern and Northeastern Plain Zones of India, indicating that their wide adoption could enhance productivity and mitigate threats from new races of rust pathogens.

Key words : Wheat, biotic and abiotic contraints, international partnership like ITAS

INTRODUCTION

Wheat is an important crop worldwide and is grown on about 210 million hectares in a range of environments, with annual production of about 620 million metric tons (FAO 2006). Less developed countries grow about 110 million hectares and produce about 307 million tons. Bread wheat (*Triticum aestivum*) is the most important wheat crop in India and worldwide followed by durum wheat (*Triticum turgidum var. durum*). Indian and global wheat production must continue to increase 2% annually until 2020 to meet future demands imposed by population and prosperity growth. Moreover, this must be achieved under reduced water availability, a scenario of global warming, stricter end-use quality characteristics, and evolving pathogen and pest populations. Most of the production growth must occur in developing countries where wheat will be consumed. Breeding wheat cultivars with increased grain yield potential, enhanced water-use efficiency, heat tolerance, end-use quality, and durable resistance to important diseases and pests can contribute to meeting at least half of the desired production increases. The remaining half must come through better agronomic and soil management practices and incentive policies. In this paper we present CIMMYT wheat germplasm improvement strategies that build upon global partnerships to address following key issues considered necessary to enhance wheat productivity in India: 1) grain yield potential and water use-efficiency, 2) durable resistance to three rusts, 3) heat tolerance, and 4) end-use quality characteristics.

SHUTTLE BREEDING AND INTERNATIONAL TESTING

One of the first things Dr. Norman E. Borlaug realized when he initiated breeding in Mexico in the 1940s was the long time required to breed new cultivars if he continued with one generation per year. This prompted him growing two crop seasons per year at two sites in Mexico, Ciudad Obregon (28°N latitude, 39 masl altitude) and Toluca (18°N latitude, 2600 masl altitude) that have very distinct photoperiods, temperatures and rainfalls during the crop seasons as well as distinct diseases. This "Shuttle Breeding" not only reduced the breeding-cycle time by half but also allowed development of widely adapted wheat germplasm. A recent simulation study comparing shuttle breeding with full selection in the field with other rapid generation advancement through doubled haploids or single-seed-descent has shown that the expected genetic gains annually is much higher with the shuttle breeding (J. Wang, unpublished).

Shuttle breeding continues to be a very powerful tool to select for traits with simple or complex inheritance at relatively low cost. CIMMYT has extended shuttle breeding between Mexico and Kenya to enable selection of complex durable, adult plant resistance to Ug99 race of stem rust pathogen that threatens wheat production globally. This strategy is probably the best option at present to enhance heat tolerance in wheat materials adapted to northwestern India.

International multi-location testing is another tool that not only allows distribution of relevant germplasm to partners in diverse environments but also determines their expected long-term performance in a single year of testing. It also allows exposing materials to a range of biotic and biotic constraints. The best performers, i.e. those with wide adaptation (Fig.1), are probably the best cultivars with

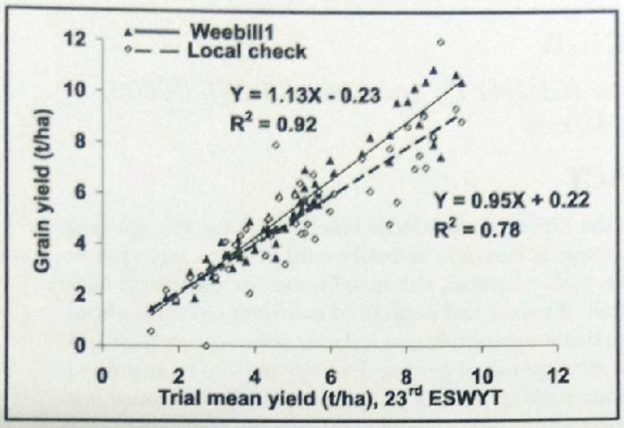

Fig. 1. Performance of bread wheat genotype 'Weebill_1' and Local Checks, regressed over trial mean at 62 international sites in 23rd ESWYT (Elite Spring Wheat Yield Trial)

least fluctuations in their performance. Exposing advanced wheat materials to hot-spot disease sites is another fast tool to stay ahead of the evolving pathogen populations. At present CIMMYT advanced breeding materials are tested at highland sites Santa Catalina, Ecuador for resistance to yellow rust and Njoro, Kenya for stem rust resistance. Partnerships with National Programs in Ecuador and Kenya thus benefits rest of the world using CIMMYT wheat germplasm.

ENHANCING GRAIN YIELD POTENTIAL AND WATER-USE EFFICIENCY

Although the early increases in yield potential of semidwarf wheat cultivars of 1970s came from the incorporation of dwarfing genes, subsequent progress can be attributed to quantitatively inherited additive genes. Intense breeding efforts during the last three decades in the post-Green Revolution era most likely have already selected additive genes of relatively larger effects contributing towards enhancing yield potential. If that is the case then further progress is expected from selecting genes that have much smaller effects, thus making it necessary to modify the commonly used traditional breeding schemes. Alternatively, introgression of new genetic diversity from unrelated wheat germplasm, including wide hybridization, can create a new genetic pool and bring in small-effect genes that may not be present in wheat germplasm commonly used in a breeding program.

MODIFYING SELECTION AND CROSSING SCHEMES TO ENHANCE THE RECOVERY OF RARE TRANSGRESSIVE SEGREGANTS

A single-backcross crossing approach that was initially applied to incorporate resistance to rust diseases based on multiple additive, minor genes, was found to favor selection of genotypes with higher yield potential as shown in Fig. 2. The reason why single backcross shifts the progeny mean toward the higher side of the curve is that it favors retaining most of the desired additive genes from the backcross or recurrent

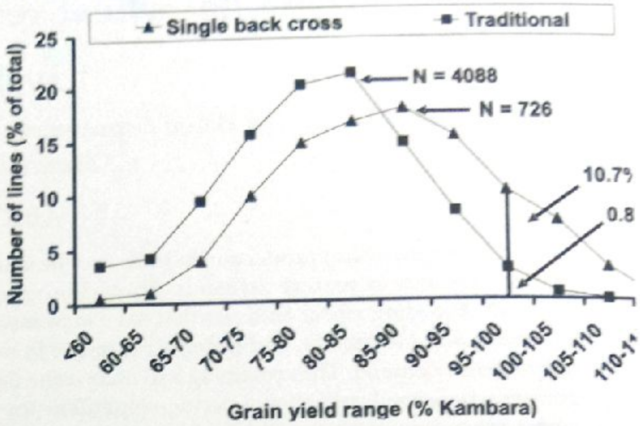

Fig. 2. Grain yield potential, expressed as %age of check cultivar 'Kambara', of 4088 advanced lines derived from traditional (simple and three-way crosses) versus 728 lines derived from single-backcross breeding approach at Ciudad Obregon, Sonora State, Mexico during 2004-2005 crop season.

parent while simultaneously allowing the incorporation and selection of additional useful small-effect genes from the donor parent. As shown in Fig. 2, the shift in mean results in higher frequency of new breeding lines that have superior yield potential than the check cultivar. Repeated backcrossing is not desirable as it was devised to incorporate a single, or few, major gene(s) with least disturbance to the genetic make-up of the recurrent parent.

Following the study by Singh *et al.* (1998b), which showed that selection schemes had little or no effect on the performance of progeny lines, but the choice of parents determined the progeny response, a selected bulk-breeding scheme was introduced in bread wheat improvement since the mid-1990s. In all segregating generations until F5 or F6, one spike from each of the selected plants is harvested as bulk and a sample of seed is used in growing the next generation. Individual plants or spikes are harvested in the F5 or F6 generation. This scheme allows retaining a larger sample of selected plants without increasing the cost and was found to be highly efficient in terms of operational costs. Moreover, retaining a large sample of plants in segregating populations increases the probability of identifying rare segregates that carry most desired genes. Cost saving in segregating generations allows yield testing of a larger number of advanced lines.

TESTING OF BREEDING MATERIALS UNDER OPTIMAL AND SUBOPTIMAL IRRIGATION CONDITIONS TO IDENTIFY FLEXIBLE GENOTYPES

As water resources are becoming limited for agricultural use either due to unavailability or increasing cost of energy and labour, it is extremely important that new wheat materials have genetic ability to give superior yields compared to the currently grown cultivars in a range of environments. Identification of recent wheat materials such as Weebill_1 (Fig. 1) with superior performance under a range of water regimes has made it possible to continue making progress selecting such flexible cultivars. Until about 2002, yield evaluations in Mexico of materials targeted for irrigated environments were conducted with five or six supplementary irrigations however such trials are now done with three or four supplementary irrigations. In addition best performing entries from the first year yield trials are also tested under one supplementary irrigation environment during the second year. These evaluations have revealed that only about a third of the advanced wheat lines maintain yield potential relative to the checks under reduced irrigation scenario. These lines are used extensively to make new cross than those that fail to maintain yield potential under limited water availability.

INCORPORATING GENETIC DIVERSITY FROM WINTER WHEATS, RELATED SPECIES AND ALIEN RELATIVES

Crossing of spring wheat germplasm with winter wheat germplasm in the 1970s and 1980s not only increased the biomass of spring wheats, but it also increased yield potential, as observed in numerous cultivars released in many countries from 'Veery' and 'Attila' crosses of CIMMYT. Although thousands of crosses were made in this effort, only the above two crosses with winter wheat parents 'Kavkaz' and 'Nord Desperez', respectively can be considered most successful as they led to the development of mega-cultivars released in East African highlands, North Africa, Middle East, Asia and Americas and subsequently grown on millions of hectares. These cultivars showed 8-10% higher yield potential over previously developed cultivars (Sayre *et al.* 1997).

Alien translocation T7DS.7DL-7Ae#1L from Thinopyrum elongatum that carries leaf and stem rust resistance genes *Lr19* and *Sr25*, respectively, has been shown to increase yield potential ranging from almost non-significant levels to over 15% depending on genetic background under irrigated conditions through increased biomass production caused by increased photosynthetic rate (Singh *et al.* 1998a, Reynolds *et al.* 2001). Thus its widespread incorporation could lead to a quantum jump in yield potential. The initial translocation carried a gene that caused higher endosperm pigmentation that is an undesirable quality trait for bread wheat. However, Knott (1980) developed a non-yellow mutant and this non-yellow variant translocation maintains the yield-enhancing effect (Huerta-Espino and Singh 2005). Wheat lines with very high yield potential in Mexico and carrying this translocation are being tested in India and other countries through the 3rd Elite Bread Wheat Yield Trial. A major effort is necessary to study the effects of various other alien translocations that have been generated. Development of molecular markers for these translocations can aid their rapid identification and incorporation and could help enhance yield potential.

Synthetic wheats, derived by crossing *Triticum turgidum* with *Aegilops tauschii* followed by embryo rescue and chromosome doubling, are being used widely in CIMMYT wheat improvement program to enhance and introduce new genes especially for stress tolerance. First generation synthetic derived wheats usually lacked some key traits to become cultivar. However, the 2nd and now the 3rd generation derivatives have started to show promise. Two wheat cultivars with synthetic wheats as parents are now released in China and Spain. An important trait derived from synthetic wheat is the better root characteristic that is probably associated with enhanced drought tolerance of synthetic wheat derivatives (Singh and Trethowan 2007).

SIMULTANEOUS SELECTION FOR GRAIN YIELD POTENTIAL AND LARGE KERNELS

Various studies have shown that increases in yield potential are mainly associated with increased biomass (Singh *et al.* 1998b, Sayre *et al.* 1997). Yield components, such as grain size and number or harvest index in more recent germplasm, have made relatively little or no contribution in explaining the increases in yield potential. This would mean that selection for increased yield potential and higher kernel weight can proceed simultaneously. Several of the recent wheat germplasm developed at CIMMYT show simultaneous increases in grain yield potential and kernel weight. It is now common to find high yielding lines with kernel weight of over 50 g/1000 kernels in the northwestern Mexico compared with about 40 g for PBW343 and most other wheat germplasm developed during the 1980s and 1990s. It is now a routine practice at CIMMYT to sieve grains of the selected bulk populations to retain plump grains, 40 mg or higher in weight

DURABLE RESISTANCE TO THREE RUSTS

Improper use of race-specific resistance genes often leads to the "Boom-and-bust" phenomenon, where soon after a cultivar occupies significant area and its resistance is overcome by a new virulent race of the rust pathogen. Cultivar replacement is usually possible only

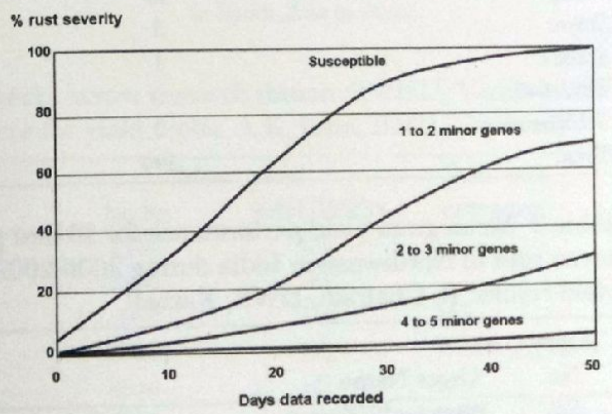

Fig. 3. Concept of durable resistance to leaf and yellow rusts in wheat: effect on number of slow rusting resistance genes in reducing disease progress

after a devastating epidemic. A major progress made in spring wheat improvement at CIMMYT has been the elucidation of the genetic basis of durable resistance to leaf and yellow rusts and the development of high yielding wheat germplasm that carries near-immune level of resistance. As shown in Fig. 3, slow rusting genes that individually have small to intermediate effects but when combined act in additive manner. Combining 4 to 5 such genes result in negligible, or near-immune, disease levels at maturity. Well characterized slow rusting genes *Lr34/Yr18/Pm38* and *Lr46/Yr29/Pm39* have turned out to have pleiotropic genetic effects. Several genomic locations are now known indicating that high genetic diversity exists for such resistance genes (Singh *et al.* 2004). A large portion of new CIMMYT germplasm now has adequate to high levels of durable resistance and their release in the future is expected to reduce threat of epidemics of leaf and yellow rusts.

Emergence and continued spread of Ug99 race of stem rust pathogen, *Puccinia graminis tritici*, has been recognized as a major threat to destabilize wheat production in many countries in its migration path because most current cultivars are susceptible (Singh *et al.* 2006). This precarious situation has led to an international response in identifying, developing and replacing current susceptible cultivars with those resistant. Recent breeding and rigorous testing of existing wheat materials at Njoro, Kenya has identified resistant wheat materials. Race-specific resistance genes *Sr22*, *Sr25* and *Sr26* are the most promising resistance genes that give effective resistance to Ug99 and its new variant that has added virulence to resistance gene *Sr24*. Some additional undesignated resistance genes such as *SrTmp*, *Sr1A.1R*, *SrND643*, *SrSha7*, *SrSynt*, etc. also contribute effective levels of resistance and are present in improved wheat materials. However, these genes are not expected to last long in areas expected to have high incidence and survival of stem rust if they are not used in combinations. Molecular markers available for some of the above genes can aid generating the combinations.

CIMMYT strategy once again is to rebuild the "*Sr2*-complex" known to confer durable adult plant resistance to stem rust in high yielding wheats rather than depending on race-specific resistance genes. Semidwarf wheat genotypes, Pavon 76, Kiritati and Kingbird, were found to carry high levels of adult plant resistance in three years of testing in Kenya. Frequency of stem rust resistant wheat materials, including those with adult plant resistance, in CIMMYT international nurseries is increasing (Table 1). New wheat lines, including some with resistance to stem rust, were evaluated at seven sites in the Northwestern India for grain yield potential during the 2006-2007 crop season. Mean grain yield performance of

Table 1 Stem rust resistance of entries included in 29thESWYT and 41stIBWSN, and entries being multiplied for probable inclusion in 30thESWYT and 42ndIBWSN.

	29thESWYT & 41stIBWSN		Mult. 30thESWYT & 42ndIBWSN	
Resistance category	Number	%	Number	%
Adult-plant:				
R (5-10% severity)	0	0.0	9	2.4
R-MR (15-20% severity)	13	6.8	38	10.3
MR (30% severity)	37	19.5	64	17.4
MR-MS (40% severity)	14	7.4	72	19.6
MS (50-60% severity)	65	34.2	83	22.6
S (70-100% severity)	44	23.2	59	16.0
Race-specific:				
Sr25	1	0.5	26	7.1
SrTmp	10	5.3	6	1.6
SrSynt	3	1.6	2	0.5
SrSha7	1	0.5	0	0.0
SrND643	0	0.0	3	0.8
SrUnknown	2	1.1	6	1.6
Total	**190**		**368**	

Table 2 Mean grain yield performance for 10 best performing entries included in the 2ndEBWYT grown at seven sites in Northwestern India during 2006-2007 crop season and their stem rust resistance (Source for yield results: R. Chatrath, DWR, Karnal).

Entry No.	Cross Name	Mean grain yield			Stem rust
		Kg/ha	Rank	%Check	category[1]
521	Waxwing*2/Kiritati	5222	1	117	MR (APR)
519	Babax/Lr42//Babax*2/3/Vivitsi	5208	2	117	MR-MS (*SrTmp*)
516	Pfau/Seri.1B//Amadina/3/Waxwing	5074	3	114	MR-MS (APR)
514	Oasis/Skauz//4*Bacanora/3/2*Pastor	5056	4	113	R-MR (*Sr25*)

513	BL2064//SW89-5124*2/Fasan/3/Tilhi	5020	5	112	MS
515	Kiritati/Weebill_1	4985	6	112	S
506	Tilhi/Pastor	4960	7	111	S
518	Munia/Chto/3/Pfau/Bow//Vee#9/4/----	4953	8	111	R-MR (?)
507	Waxwing*2/Tukuru	4952	9	111	MS
504	Milan/S87230//Babax	4930	10	110	S
501	Check = PBW502 (6 sites), PBW343 (1 site)	4472	27	100	MS
	LSD, P= 0.05	410.1			
	CV (%)	11.1			

[1]Stem rust categories are APR = Adult Plant Resistance, R-MR = Resistant-Moderately Resistant (15-20% final severity), MR = Moderately resistant (30% final severity), MR-MS = Moderately Resistant-Moderately Susceptible (40% final severity), MS = Moderately Susceptible (50-60% final severity), and S = Susceptible (70-100% final severity).

entries with 10% or higher yields over the checks PBW502 or PBW343 are given in Table 2. The top four performers with 13-17% higher yields are lines that have adequate resistance to Ug99 race of stem rust. The top performing entry Waxwing*2/Kiritati not only has adult plant resistance but also has excellent end-use quality. These high yielding materials with diverse resistance should be promoted to reap the benefit from increased yield potential while reducing the Ug99 threat. A Mexico-Kenya shuttle breeding scheme was also established in 2006 to enhance the frequency of plants with adult plant resistance in segregating populations.

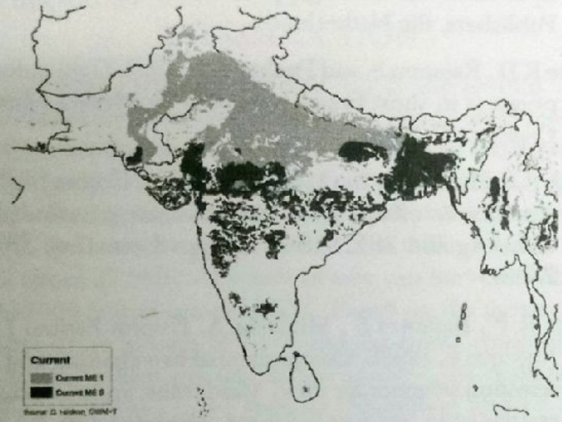

Fig. 4a. Map showing the current distribution of favorable and heat-stressed wheat mega-environments ME1 and ME5 in South Asia.

ENHANCING YIELD POTENTIAL OF EARLY MATURING WHEATS TO ESCAPE POST-FLOWERING HEAT STRESS

Early maturity is an important trait to avoid excessive heat at grain filling. As shown in Fig. 4a the Northeastern Gangetic Plains, Central and Peninsular zones in India are classified as current heat stressed environment and this region is predicted to expand to Northwestern Gangetic Plains covering most of it by 2050 (Fig. 4b). All currently grown popular cultivars in heat stressed areas are earlier maturing than cultivars popular in the Northwestern Gangetic

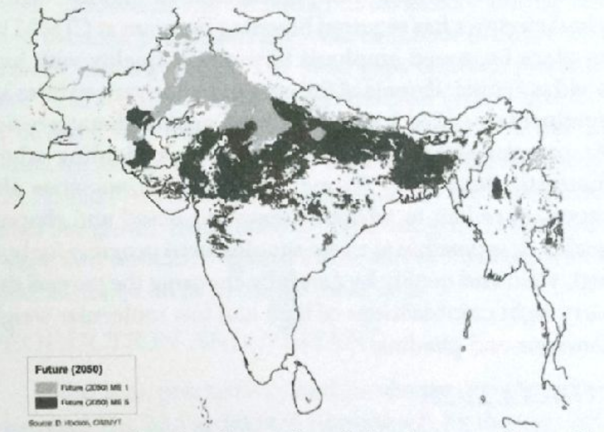

Fig. 4b. Map showing the predicted distribution of favorable and heat-stressed wheat mega-environments ME1 and ME5 in South Asia in 2050.

Table 3 Performance of nine early maturing lines and checks across research station of BHU, Varanasi and eight farmers' fields during 2006-2007 crop season (Source for yield reults: A.K. Joshi, BHU, Varanasi).

Variety/Cross	Mean yield kg/ha	Mean yield %HUW234	Stem rust category[1]
HUW 234 (Check)	3510	100	
HUW 468 (Check)	3490	99	
Waxwing*2/Tukuru	4080	116	MS
Waxwing*2/Vivitsi	3980	113	R-MR (APR)
Kiritati//Attila*2/Pastor	3940	112	MS
Kiritati/4/Seri.1B*2/3/Kauz*2/Bobwhite//Kauz	3910	111	MS
Kiritati//HUW234+*Lr34*/Prinia	3890	111	MR
BAJ	3840	109	MS
Kiritati//Parula/2*Pastor	3810	109	MS

PfauSeri.1B//Amadina/3/Waxwing	3810	109	S
Weaver/Transec//Weaver/3/Weaver/4/Parula/2*Pastor	3730	106	S
Kiritati/Weebill_1	3720	106	S

[1]Stem rust categories are APR = Adult Plant Resistance, R-MR = Resistant-Moderately Resistant (15-20% final severity), MR = Moderately resistant (30% final severity), MS = Moderately Susceptible (50-60% final severity) , and S = Susceptible (70-100% final severity).

Plains. A simultaneous improvement of heat tolerance and yield potential of earlier maturing germplasm is the only option to increase production in heat stresses environment. Yield performance of ten new early maturing, high yielding CIMMYT lines in Northeastern Gangetic Plains during 2006-2007 season (Table 3) shows that our simple breeding strategy has resulted in the identification of new wheat lines that show 10-15% higher yields over the popular cultivars. Two of these higher yielding entries, Kiritati//HUW234+*LR34*/Prinia and Waxwing*2/Vivitsi, are also resistant to Ug99 race of stem rust pathogen. To achieve further progress, a shuttle breeding between Mexico and heat stressed sites in India must initiate as soon as possible.

IMPROVING END-USE QUALITY CHARACTERISTICS

Increasing demands from industries, supermarkets and consumers for better quality of bread, chapatti and other products as well as higher prices for grain produced from wheat varieties that possess desired end-use quality characteristics has required breeding program at CIMMYT to place increased emphasis to combine quality with high yield potential. Parents of the crosses and advanced lines are routinely classified for their end use quality characteristics. At present about a quarter of the high yielding wheat materials distributed through international nurseries also carries excellent to adequate leavened bread and chapatti quality. It is possible to make simultaneous progress for both high yield and quality by carefully choosing the parents that carry right combinations of high and low molecular weight glutenins and gliadins.

CONCLUSION

Genetic progress towards increasing yield potential together with accumulating diverse genes for other important traits is evident in new international spring wheat germplasm relevant to enhancing productivity and mitigating the threat of rust diseases. This has been possible through strong global collaborations and partnerships. Sharing of wheat germplasm and new partnerships with shared responsibilities will be necessary in the future to continue making further and faster progress.

REFERENCES

FAO. 2006. Statistical database. www.fao.org.

Huerta-Espino J and Singh R P. 2005. Effects of 7DL.7Ag (mutated for reduced flour yellowness) and 4BL.2R translocations on grain yield of wheat under irrigated and stressed environments. In Abstr. of 7th International Wheat Conference: Wheat Production in Stressed Environments, Nov 27-Dec. 2, Mar del Plata, Argentina, pp. 339.

Knott D R. 1980. Mutation of a gene for yellow pigment linked to *Lr19* in wheat. *Can. J. Genet. Cytol.* **22**:651-654.

Reynolds M P, Calderini D F , Condon A G and Rajaram S. 2001. Physiological basis of yield gains in wheat associated with the *Lr19* translocation from Agropyron elongatum. In Wheat in a Global Environment, edited by Z. Bedo and L. Lang, pp. 345-351. Kluwer Academic Publishers, the Netherlands.

Sayre K D , Rajaram S and Fischer R A. 1997. Yield potential progress in short bread wheats in Northwest Mexico. *Crop Sci.* **37**: 36-42.

Singh R P, Huerta-Espino J , Rajaram S and Crossa J. 1998a. Agronomic effects from chromosome translocations 7DL.7Ag and 1BL.1RS in spring wheat. *Crop Sci.* **38**: 27-33.

Singh R P , Rajaram S , Miranda A, Huerta-Espino J and Autrique E. 1998b. Comparison of two crossing and four selection schemes for yield, yield traits, and slow rusting resistance to leaf rust in wheat. *Euphytica* **100**: 35-43.

Singh R P and Trethowan R. 2007. Breeding spring bread wheat for irrigated and rainfed production systems of developing world. Pages 109-140, in: M. Kang and P.M. Priyadarshan (eds.). Breeding Major Food Staples. Blackwell Publishing.

Singh R P, William H M , Huerta-Espino J and Rosewarne G. 2004. Wheat rust in Asia: meeting the challenges with old and new technologies. In "New Directions for a Diverse Planet: Proceedings of the 4th International Crop Science Congress", http://www.cropscience.org.au./icsc2004/symposia/3/7/141_singhrp.htm (accessed on November 29, 2007). September 26 – October 1, 2004. Brisbane, Australia.

Singh R P , Hodson D P , Jin Y, Huerta-Espino J , Kinyua M , Wanyera R , Njau P and Ward R W. 2006. Current status, likely migration and strategies to mitigate the threat to wheat production from race Ug99 (TTKS) of stem rust pathogen. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 1, No.54.