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Climate change: Can wheat beat the heat?

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Abstract

Climate change could strongly affect the wheat crop that accounts for 21% of food and 200 million hectares of farmland worldwide. This article reviews some of the approaches for addressing the expected effects that climate change may likely inflict on wheat in some of the most important wheat growing areas, namely germplasm adaptation, system management, and mitigation. Future climate scenarios suggest that global warming may be beneficial for the wheat crop in some regions, but could reduce productivity in zones where optimal temperatures already exist. For example, by 2050, as a result of possible climate shifts in the Indo-Gangetic Plains (IGPs) – currently part of the favorable, high potential, irrigated, low rainfall mega-environment, which accounts for 15% of global wheat production – as much as 51% of its area might be reclassified as a heat-stressed, irrigated, short-season production mega-environment. This shift would also represent a significant reduction in wheat yields, unless appropriate cultivars and crop management practices were offered to and adopted by South Asian farmers. Under the same climate scenarios, the area covered by the cool, temperate wheat mega-environment could expand as far as 65°N in both North America and Eurasia. To adapt and mitigate the climate change effects on wheat supplies for the poor, germplasm scientists and agronomists are developing heat-tolerant wheat germplasm, as well as cultivars better adapted to conservation agriculture. Encouraging results include identifying sources of alleles for heat tolerance and their introgression into breeding populations through conventional methods and biotechnology. Likewise, agronomists and extension agents are aiming to cut CO_2 emissions by reducing tillage and the burning of crop residues. Mitigation research promises to reduce emissions of nitrous oxide by using infrared sensors and the normalized differential vegetative index (NDVI) that determines the right times and correct amounts of fertilizer to apply. Wheat geneticists and physiologists are also assessing wild relatives of wheat as potential sources of genes with inhibitory effects on soil nitrification. Through the existing global and regional research-for-development networks featuring wheat, technology and knowledge can flow to allow farmers to face the risks associated with climate change.

Keywords: *Triticum aestivum*; Climate change; Conservation agriculture; Genetic enhancement; Mega-environment; Wheat

1. Introduction

About 21% of the world's food depends on the wheat (*Triticum aestivum*) crop, which grows on 200 million hectares of farmland worldwide (http://www.fao.org). Although wheat is traded internationally and developing countries are major importers (43% of food imports), the reality is that 81% of wheat consumed in the developing world is produced and utilized within the same country, if not the same community (CIMMYT, 2005). In these circumstances, many poor households depend on increased wheat production on their own farms for improved household food security. In the period leading up to 2020, demand for wheat for human consumption in developing countries is expected to grow at 1.6% per annum, and for

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feed at 2.6% per annum. The global average wheat yield will have to increase during the coming 25 years from 2.6 to 3.5 tonnes ha^{-1}. This yield increase, essential to maintain global food security, requires a continuing supply of improved germplasm and appropriate agronomy in order to sustain enhanced productivity and preserve the natural resource base. However, global warming, as a result of climate change, may negatively affect wheat grain yields—potentially increasing food insecurity and poverty, although it should be noted that current effects of climate change in relation to wheat are inconclusive and model-dependent (Tubiello et al., 2000). More recent and extensive research on climate change effects predicts marked increases in both rainfall and temperature, with temperatures projected to rise by as much as 3–4 °C by the end of the century in South Asia (DEFRA, 2005). Predicted effects on wheat production include reduced grain yield over most of India, with the greatest impacts in the lower potential areas, for example in the eastern plains. Multiple cropping systems involving wheat often maximize profitability of the non-wheat cash crop components resulting in delayed sowing of wheat, subjecting it to sub-optimal, often hotter, growing seasons. In the rice–wheat system of eastern India, remote sensing studies revealed at least 60% of district wheat areas were sub-optimally, late planted (Chandna et al., 2004).

In many of the dry environments that suffer today from severe heat stress during grain filling, it has been shown that the enzyme soluble starch synthase in wheat appears to be rate limiting at temperatures in excess of 20 °C (Keeling et al., 1994). Furthermore, the grain filling of wheat is seriously impaired by heat stress due to reductions in current leaf and ear photosynthesis at high temperatures (Blum et al., 1994). Nonetheless, as shown by Blum et al. (1994), in some wheat lines grain filling from mobilized stem reserves is a constitutive trait, which supports grain filling under heat stress which can be tested for by chemical desiccation of plants in non-heat-stressed environments.

Throughout the 1980s and 1990s the Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) together with partners in the developing world, undertook wheat research in heat-stressed, dry areas and rice–wheat farming systems (Saunders and Hettel, 1994). A series of proceedings ensued from international conferences held to address wheats for more tropical environments (CIMMYT, 1985), constraints to wheat production in such environments (Klatt, 1988), and adapting wheat to non-traditional warm areas (Saunders, 1991). This article reviews and updates some of these approaches for addressing the expected effects that climate change may likely inflict on wheat in some of the most important wheat growing areas, namely germplasm adaptation, system management, and mitigation. Indeed, to address the effect of climate change, a research-for-development agenda should follow a holistic approach that brings together genetic improvement, crop management, capacity building and knowledge sharing.

2. The mega-environment concept

Researchers work across disciplines to provide appropriate technology options for farmers in diverse settings of the developing world. One framework for these efforts is a series of wheat ‘‘mega-environments’’ (MEs) delineated by CIMMYT. Mega-environments are broad, often non-contiguous or transcontinental areas with similar biotic or abiotic stresses, cropping systems, consumer preferences and volume of production (Table 1) (Braun et al., 1996). For example, ME-1 includes 32 million hectares of low moisture but irrigated land mainly in northwest Mexico, the Indo-Gangetic Plains (IGPs) and the Nile Valley with a temperate climate in which rusts are today the mains biotic stresses.

In addition to helping properly target seed-embedded or resource-conserving crop management technologies, the mega-environments also allow CIMMYT to monitor impacts and changes of cropping patterns or crop land uses, as productivity factors change. For example, advanced genotype by environment analysis has been recently published on the High Temperature Wheat Yield Nursery that encompassed putative heat-tolerant advanced lines developed by CIMMYT between 1992 and 2000 and grown at 101 locations worldwide that vary in temperature profile (Lillemo et al., 2005). This analysis represents an excellent platform for determining the localization of comprehensive environmental characterizations that will help wheat researchers worldwide target germplasm for specific environments. Indeed, important factors influencing differing heat stress patterns are highlighted in their research and may provide a basis for in-depth spatial and temporal characterization of discrete heat-stress environments, which require differing germplasm adaptation patterns. The increasing availability of spatially and temporally disaggregated climatic variables data, coupled with geographic information system (GIS) tools, would further form the basis to advance current general classifications of a single static heat-stress environment to determine spatial extents and frequencies of the differing heat-stress environments.

3. Long-term monitoring of wheat yield potential and assessing climate influence

The monitoring of crop trends provides a means for assessing the influence of climate in the crop(s) being grown (Bell and Fischer, 1994; Lobell et al., 2005). For example, wheat production in the Yaqui Valley of Sonora in northwest Mexico (a representative location of wheat mega-environment 1) has been regularly and accurately recorded for total annual planted and harvested area, total and farm-level production levels and consequently, the average farm-level yields over the valley and at the level of individual farmer fields. Fig. 1 shows the yield trend from 1951 to 2005 and includes the plot of the actual yields and yields predicted by quadratic regression. As can be observed, from 1951 to

Table 1
Wheat mega-environments (ME) and their main features

ME	Area (million hectares)	Moisture regime	Temperature regime	Main breeding Targets	Main locations in developing world	Breeding started at CIMMYT
1	32	Low irrigated	Temperate	Lodging rusts	Northwest Mexico, Indo-Gangetic Plains, Nile Valley	1945
2	10	High rainfall	As above	As above + *Septoria*, sprouting	Mediterranean litoral, the Andes, East Africa and Toluca, Mexico	1972
3	1.7	As above	As above	ME-2 + acid soil	Passo Fundo, Brazil	1974
4A	10	Low winter dominant	As above	Drought *Septoria* yellow rust	Aleppo, Syria Settat, Morocco	1974
4B	5.8	Low summer	As above	Drought *Septoria* leaf + stem rusts *Fusarium*	Marco Juárez, Argentina	1974
4C	5.8	Residual	Hot	Drought + heat seedlings	Indore, India	1974
5A	3.9	High rain-fall, humid irrigated	Hot	Heat *Helminthos-porium*	Joydepur, Bangladesh Londrina, Brazil	1981
5B	3.2	Irrigated low humidity	Hot	Stem rust heat	Gezira, Sudan Kano, Nigeria	1975
6	5.4	Moderate rainfall summer	Temperate	Stem + leaf rusts *Helminthosporium Fusarium* sprouting photo-period sensitivity	Harbin, China	1980
7		Irrigated	Moderate cold	Rapid grain filling, yellow rust, cold tolerance, powdery mildew, barley yellow dwarf virus	Zhenzhou, China	1986
8A		High rainfall, irrigated, short season	Moderate cold	Cold tolerance, yellow rust, *Septoria*	Chillán, Chile	1986
8B		High rainfall, irrigated, short season	Moderate cold	*Septoria*, yellow rust, powdery mildew, *Fusarium*, sprouting	Edirne, Turkey	1986
9		Low rainfall	Moderate cold	Cold tolerance, drought	Diyarbakir, Turkey	1986
10		Irrigated	Severe cold	Winter killing tolerance, yellow + leaf rusts, powdery mildew, barley yellow dwarf virus	Beijing, China	1986
11A		High rainfall, irrigated, long season	Moderate cold	*Septoria*, *Fusarium*, yellow + leaf rusts, powdery mildew	Temuco, Chile	1986
11B		High rainfall, irrigated, short season	Severe cold	Leaf + stem rusts, powdery mildew, winter killing tolerance, sprouting	Lovrin, Romania	1986
12		Low rainfall	Severe cold	Winter killing tolerance, drought, yellow rusts, blunts	Ankara, Turkey	1986

Spring wheat grows in mega-environments 1–6 whereas facultative wheat grows in mega-environments 7–9, and winter wheat in mega-environments 10–12. All ME except 6 are autumn sown (after Braun et al., 1996).

about 1975, yields increased in a linear manner but in subsequent years, the rate of yield increase has declined.

The rate of average wheat yield increase in farmer fields in the Yaqui Valley over the whole time period from 1951 to 2005 has been impressive (Table 2), which is representative of similar rates of yield increase that have occurred in many other wheat production areas such as India, Pakistan and China among many others (especially irrigated production regions), notably since the introduction and adoption of semi-dwarf cultivars with resistance to the various rust diseases (Reynolds and Borlaug, 2006). However, there is a clear tendency towards a reduced rate of yield increase over time. This is a fact of considerable concern and is likely not restricted to the Yaqui Valley.

Table 2 also provides an excellent example of how statistics of this nature can be potentially used to ill effect. It appears that there was a large rate of yield increase over the 1991–2000 period. However, there have been considerable annual yield fluctuations due mainly to variations in weather from crop season to crop season (Fig. 1). The 1990–1991 crop cycle was characterized by extreme high rainfall with associated high minimum air temperatures and low radiation from December 1990 to March 1991 (an example of the effects of a severe El Niño event in northwest Mexico) resulting in the lowest average wheat yield in farmer yields compared to the 15 previous years. The yields, however, for the subsequent 10 years were considerably higher thereby providing the appearance of a marked increase in yields over this 10-year period.

There is evidence that the minimum air temperatures have been ‘‘above normal’’ during several winter crop cycles over the past 15 years (attributed by some to the global

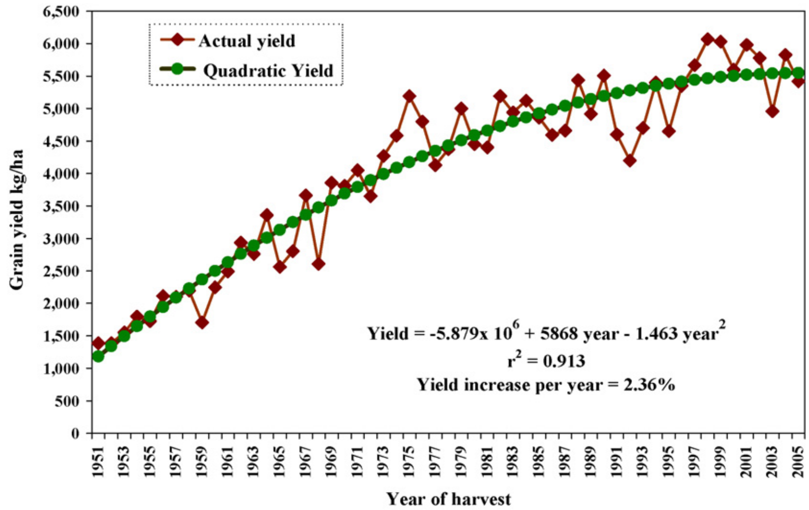

Fig. 1. Wheat yield trend from 1951 to 2005 in the Yaqui Valley of Sonora, Mexico.

Table 2
Annual rates of increase in average farmer wheat yields in the Yaqui Valley (Sonora, northwest Mexico) for defined periods and breeding eras from 1951 to 2005

Time period	Yield increase per year (%)	Yield increase per year (kg ha^{-1})	R^2 (year-X versus grain yield-Y)
1951–2005	2.36	81	0.857
1951–1960	4.98	88	0.664
1961–1970	3.51	113	0.410
1971–1980	1.69	72	0.220
1981–1990	1.08	54	0.207
1991–2000	3.56	182	0.727
1991–2005	1.64	83	0.397
Breeding eras			
1951–1962 (introduction of improved, non–semi-dwarf cultivars)	5.79	115	0.788
1963–1975 (introduction of initial semi-dwarf cultivars)	4.81	175	0.732
1976–2005 (current improvement efforts for semi-dwarf cultivars)	0.85	43	0.439

warming due to the climate change phenomenon), which have contributed additionally to the reduction in potential wheat yield expression. Several low yielding years from 1995 to 2005 were associated with high minimum temperatures during cloudy periods from January to March and corresponding low radiation levels (Fig. 1). Research in the Yaqui Valley has demonstrated that high wheat yields are strongly associated with low average temperatures (especially low average minimum temperatures; Lobell et al., 2005) and high radiation levels for a period of 30 days (20 days prior to anthesis and 10 days post-anthesis). The above results suggest that new sources of genetic variation combined with more efficient breeding and selection methods must be pursued further to ensure significant increases in genetic yield potential for spring bread and winter wheat cultivars (Ortiz et al., 2007).

4. Modeling climate change in wheat-cropping areas

Coupling crop simulation models to predicted future climate scenarios is one approach taken to determine the impacts of climate change in agriculture. For example, Jones and Thornton (2003) forecast for 2055 an overall 10% reduction on maize production in Africa and Latin America; i.e., a loss in maize grain worth approximately US $2 billion yearly. An alternative, more general approach is to examine potential changes in major production environments.

The map in Fig. 2 illustrates today's wheat producing areas in the plains of the Indo-Ganges, which account for approximately 90 million tonnes of grain (about 14–15% of global production). The mega-environment (ME) zonation, used to classify wheat-growing regions into relatively homogenous environments requiring similar adaptation

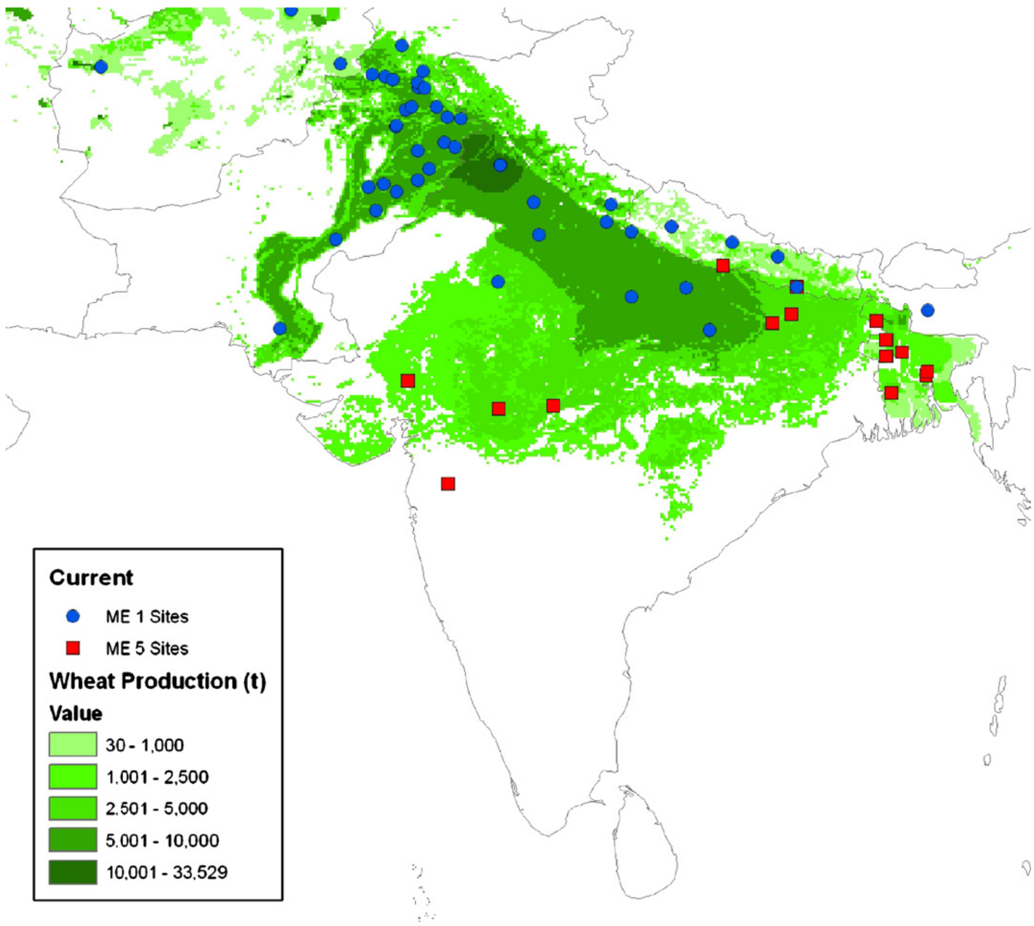

Fig. 2. Current wheat production zones in the Indo-Gangetic Plains with major trial sites classified by mega-environment (ME).

indicated two main wheat environments in the Indo-Ganges: mega-environment 1 is a favorable, irrigated, low rainfall environment with high yield potential whereas mega-environment 5 is a heat-stressed environment (early and late season heat stress) with available irrigation but in its humid and hot areas, the fungus *Bypolaris sorokiniana* is the causal agent of *Helminthosporium* leaf blight. Using site classification data, in combination with long-term normal climate data and irrigated area data, potential mega-environment zones were updated and delineated on an agro-climatic basis (White et al., 2001). These two major wheat mega-environments in the sub-continent have been differentiated on the basis of coolest quarter minimum temperature ranges (3–11 °C for ME-1 and 11–16 °C for ME-5). In some of the mega-environment 5 areas poorer infrastructure, socio-economic factors, and crop management coupled with the stresses brought by *Helminthosporium* leaf blight and the shortened vegetative phase ensuing from heat stress, particularly at grain filling, lead to low yield in wheat, whose quality may be also affected by grain shriveling.

Fig. 3 shows the mega-environment zonation for the IGP under current and future climate scenarios. The future scenario (Fig. 3b) is based on a doubling of CO_2 using a CCM3 model (Govindasamy et al., 2003) and downscaled to a 30 arc-second resolution as part of the Worldclim data set (Hijmans et al., 2004). Under this future scenario and ME classification, there is a 51% decrease of the most favorable and high yielding mega-environment 1 area due to heat stress, thereby leading to likely yield losses of the wheat grain harvest. Unless appropriate improved germplasm, crop husbandry and resource management are deployed, about 200 million people (using current population), whose food intake relies on crop harvests in mega-environment 1, will be more vulnerable due to this heat stress affecting wheat-cropping systems.

The high latitude wheat-cropping systems are included in mega-environment 6—this is defined climatically as areas with coolest quarter minimum temperature above −13 °C and the warmest quarter minimum temperature below 9 °C. This ME comprises the cool temperate regions of North America and northern Eurasia, where wheat is spring sown because winters are too severe for the survival of winter wheat. Today North American farmers grow wheat up to 55°N, but under the 2050 (doubling of CO_2) scenario the North American mega-environment 6 may shift northwards

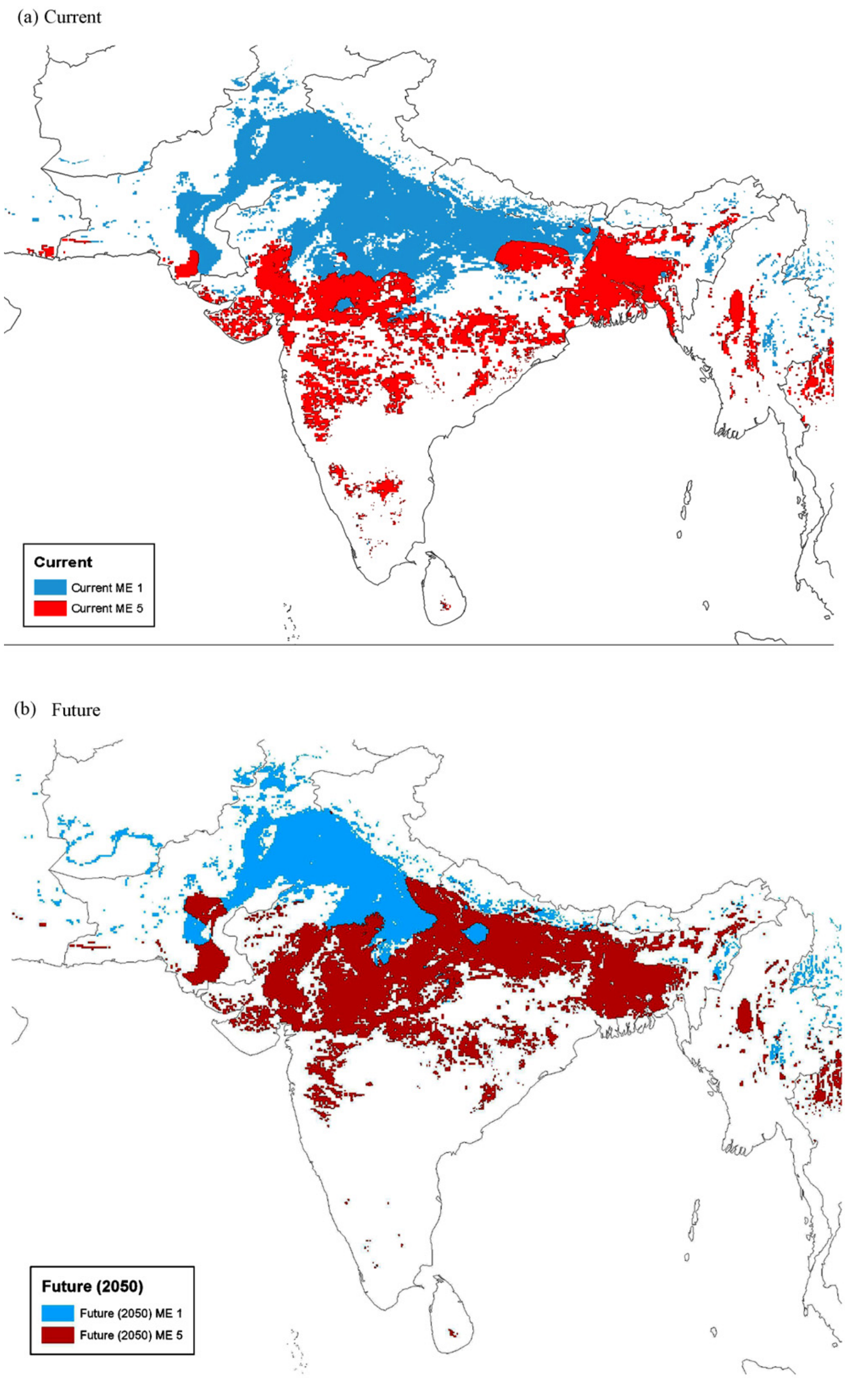

Fig. 3. Current and future potential wheat mega-environments in the Indo-Gangetic Plains.

(Fig. 4): up to 65°N due to a positive warming benefit ensuing from climate change. This may affect northern Eurasia; in a similar way i.e., major expansion of potential wheat growing areas based solely on climatic factors, although with no consideration of other factors such as suitable soils, land use (e.g. forestry or protected areas) or infrastructure.

5. Adapting wheat to heat-prone environments

Clearly, wheat yield in lower latitudes may decrease as per the above global warming forecast, which may be further affected by water scarcity or drought. One approach to dealing with these heat-related constraints is to improve wheat germplasm to provide higher tolerance to stresses associated with these environments. Hence, wheat breeders should start genetically enhancing the crop to maintain yield under higher temperatures using all available means in the tool kit. In this way, they will assist in building cropping system resilience to the global warming hazards that could jeopardize the livelihoods of resource-poor farmers who depend on the wheat harvest.

About 9 million hectares of wheat grow in tropical and subtropical areas of the developing world with temperatures above 17 °C in the coolest month of the growing season. The heat-stressed environments are divided into separate agro-ecozones within their respective mega-environment to better target wheat breeding. They are split according to high or low relative humidity; e.g. humid sites in Bangladesh, lowland Bolivia, Brazil, eastern India, Terai of Nepal, Paraguay, Thailand or Uganda, and dry sites in Egypt, central and peninsular India, Nigeria, Sudan or Syria (Lillemo et al., 2005). White et al. (2001) used a GIS-based assessment in Ethiopia with emphasis on climate factors limiting wheat potential areas. Their appraisal considered mainly agro-climatological data from interpolated climate data contained in the Ethiopian Country Almanac. Their results suggest that the greatest opportunity to expand wheat production in Ethiopia may come by increasing heat tolerance in wheat but that other factors, including the adaptation of current or alternate crops, overall land-use suitability, and market constraints must be considered before moving wheat into any new areas.

Grain growth appears to be shorter under heat irrespective of daylength sensitivity or vernalization needs (Midmore et al., 1982). Likewise, in heat stress already affects wheat plant senescence and photosynthesis (Al-Khatib and Paulsen, 1984), thereby influencing grain filling (Wardlaw et al., 1980). Wheat cultivars capable of maintaining high 1000-kernel weight under heat stress appear to possess higher tolerance to hot environments (Reynolds et al., 1994). Physiological traits that are associated with wheat yield in heat-prone environments are canopy temperature depression, membrane thermo-stability, leaf chlorophyll content during grain filling, leaf conductance and photosynthesis

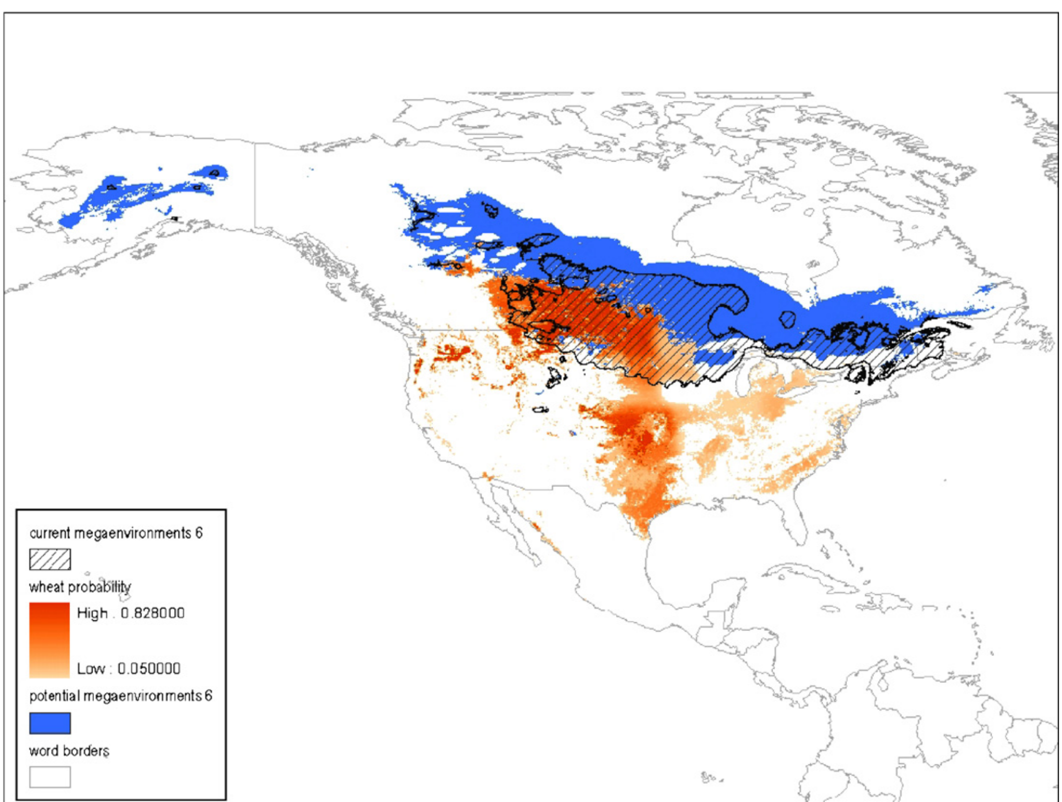

Fig. 4. Global warming and potential northward expansion of wheat mega-environment 6 in North America (2050).

(Reynolds et al., 1998). Amani et al. (1996) used canopy temperature depression to select for yield under a hot, dry, irrigated wheat environment in Mexico, whereas Hede et al. (1999) found that leaf chlorophyll content was correlated with 1000-kernel weight while screening Mexican wheat landraces. Such sources of alleles coupled with some of the above traits can provide means for genetically enhanced wheat by design in heat-prone environments. In this regard, data from extensive international yield trials in more marginal environments indicate even greater grain yield progress (2–3% per annum) in both semi-arid and heat-stressed environments between 1979 and 1995 (Trethowan et al., 2002).

Multidisciplinary research involving genetic resources enhancement and crop physiology at CIMMYT have led to a physiological trait-based approach to breeding for abiotic stress which has merit over breeding for yield *per se* by increasing the probability of successful crosses resulting from additive gene action. Advances have already been made in the drought-breeding program (Reynolds and Borlaug, 2006; Ortiz et al., 2007), and this strategy will be used to breed wheat for the high temperature-stressed environments.

6. Conservation agriculture can help adapt wheat-cropping systems to climate change

Wheat yields in warm environments can be raised significantly by modifying agronomic practices (Badaruddin et al., 1999). Conservation agriculture involves significant reductions in tillage, surface retention of adequate crop residues, and diversified, economically viable crop rotations. Along with other resource-conserving farming practices, conservation agriculture can improve rural incomes and livelihoods by reducing production costs, managing agro-ecosystem productivity and diversity more sustainably, and minimizing unfavorable environmental impacts, especially in small and medium-scale farms (Kataki, 2001). One of the chief longer term productivity benefits of conservation agriculture practices would be to reverse the widespread, chronic soil degradation (Lal, 2004a) that threatens yields in intensive wheat-cropping systems like those of the Indo-Gangetic Plains in South Asia. Degraded soils and dwindling water supplies threaten the region's productivity for about 300 million people who depend on rice–wheat-cropping rotations for food and livelihoods (Ladha et al., 2003).

Ortiz-Monasterio et al. (1994) described the dramatic yield-reducing effects of high temperatures around and after heading, for the wheat crop in South Asia. Resource-conserving practices like zero-tillage (ZT) can allow rice–wheat farmers to sow their wheat sooner after rice harvest, so the crop heads and fills the grain before the pre-monsoon hot weather ensues. As average temperatures in the region rise, early sowing will become even more important for wheat.

Resource-conserving practices also bring many environmental benefits. For example, using zero-tillage for wheat on 1 ha of land in the rice–wheat-cropping systems of the IGP can save 1 million liters of irrigation water and 98 liters of diesel fuel, as well as reducing carbon dioxide emissions by 0.25 tonnes (Reeves et al., 2001).

Adoption of conservation agriculture and other resource-conserving practices depends on farmer knowledge and the availability of appropriate machinery. Regional scaling-up of zero-tillage for wheat in the IGP came after extensive on-station and on-farm testing of suitable minimum-tillage management, as well as investments for designing local, effective, and affordable seeding and tillage equipment. This and other resource-conserving technologies are being used by progressive farmers on about 1.3 million hectares in the region, thereby lowering land preparation costs, increasing farmer incomes, and resulting in the production of some 0.46 million tonnes of additional food (Table 3; Fig. 5). The Rice–Wheat Consortium for the Indo-Gangetic Plains (http://www.rwc.cgiar.org/) played a key role in testing and promoting these practices with farmers, and in 2004 the consortium received the King Baudouin Award of the Consultative Group for International Agricultural Research (CGIAR), in recognition of its efforts.

The above successes show how resource-conserving farming practices can contribute to productivity, poverty alleviation, food security, and environmental improvements. In South Asia, appropriate alternatives are still needed to reduce significantly the extensive tillage, puddling, and transplanting of rice in rice–wheat systems, thereby reducing the CO_2 and methane emissions associated with continuously flooded rice paddies. In addition, there are strong genotype × tillage interactions that affect the development of conservation agriculture practices for wheat and other cropping systems (Trethowan et al., 2005). Plant breeders need to improve wheat for conservation agriculture systems, especially zero- and minimum-tillage. Traits of interest include better water productivity, improved root health, and resistance to pests that emerge in residues or result from adoption of conservation agriculture practices.

7. Long-term conservation agriculture trials and gaining climate change insights

It is essential to have an indication of the sustainability of an agricultural system before the catastrophic consequences of non-sustainability become apparent. Long-term field experiments with contrasting treatments offer the best way to test sustainability (Powlson and Johnston, 1994). Long-term trials are defined as large-scale field experiments more than 20 years old that study cropping system dynamics and their impacts on agriculture and the environment (Rasmussen et al., 1998). CIMMYT started about two decades ago various long-term agronomical trials at its experimental

Table 3
The adoption of resource-conserving practices in South Asia (2001–2004)

Zero-tillage	Districts			Area (ha) coverage			Number of farmers		
	2001	2002	2003	2001	2002	2003	2001	2002	2003
Uttar Pradesh (W)	11	22	2	11,800	40,900	175,000	7300	16,500	50,000
UP, Uttranchal and HP	16	18	2	820	4270	60,000	700	3200	36,000
Bihar	8	10	1	380	1000	18,000	1000	1700	6000
Haryana	10	10	12	97,166	275,000	350,000	15,000	52,000	70,000
Punjab India	8	13	14	20,000	50,000	215,000	3000	8000	46,700
Pakistan Punjab	16	16	16	78,408	189,980	335,000	10,281	26,574	47,900
Pakistan Sind/	2	3	3	132	397	1100	11	32	100
Nepal	6	6	6	32	76	2100	35	70	1500
Bangladesh	3	3	–	4	10	10	5	10	10
Total	80	101	113	208,742	561,033	1,156,210	37,332	107,686	258,210
2-Wheel HT									
Nepal Tarai	6	–	N	120	–	N	N	100	N
Bangladesh	10	N	N	363	N	500	N	150	N
Total	16			483				250	
Bed planting									
Uttar Pradesh (W)	11	16		1330	2840[a]	20,000	200	780	8000
Uttar Pradesh (E)	16	16		50	126	100+	10	34	50
Bihar	1	2	3	4	125[a]	50+ 200P	10	125	150
Haryana	11	11		1000	400	1000	50	35	100
Punjab India	12	12		1000	1700	10,800	50	73	250+
Pakistan Punjab	9	9	9	1312	1750	2800	64	80	160
Nepal	3	3		5	27	–	8	21	–
Bangladesh	3	3	3	5	25	50	5	23	50
Total	73	78		4706	6993	35,000	397	1171	
Surface seeding									
Bangladesh	5	5		10,000[b]	10,000[c]	N	30,000	30,000	N
Nepal	4	2		223	457	N	132	262	N
Eastern India	3	4		500	560	20,000	1000	105	–
Total	12	11		10,723	11,117	20,000	31,132	31,312	

[a] Area under intercrops and vegetable crops.
[b] Frequency depends on seeding conditions; estimates of last WRC survey indicated up to 10,000 ha when conditions were favorable.
[c] Frequency depends on seeding conditions; estimates of last WRC survey indicated up to 10,000 ha when conditions were favorable.

stations. Such trials are research platforms for assessing crop husbandry and natural resource management. The resulting raw data can also be used to develop, validate, and test crop and cropping system models.

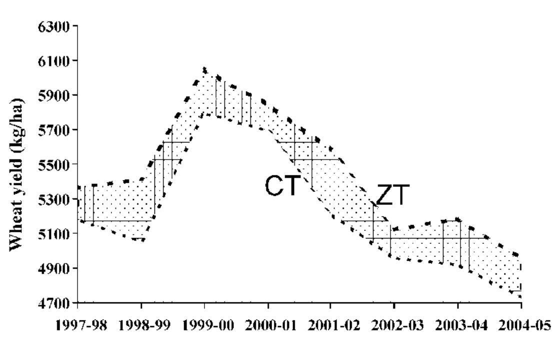

Fig. 5. Yield gains in wheat by adopting zero-tillage (ZT) in the Indo-Ganges: about 247 kg ha^{-1} (shade area) on average were added to land previously under conventional tillage (CT).

7.1. *Permanent beds and residue retention under irrigation: potential for carbon sequestration*

Conservation agriculture in its version of permanent bed planting under zero-tillage with crop residue retention has been proposed as an alternative wheat production system for northwest Mexico. Reduced tillage systems offer advantages over conventional tillage (CT), reducing costs and conserving soil and water. However, little is known about the dynamics of carbon (C) and nitrogen (N) in soils under wheat-maize cropping on permanent beds (PBs), where straw was burned, removed, partly removed or retained, as opposed to conventionally tilled beds (CTBs) where straw was incorporated. After more than 20 successive crops of wheat and maize under permanent beds or conventional tilled beds, residue management and N fertilizer applications had a significant effect on topsoil organic C and total N. The organic C and total N were significantly (1.15 and 1.17 times) greater in PB-straw partly removed and PB-straw retained, than in CTB-straw incorporated (Govaerts et al., 2006a).

7.2. Zero-tillage and residue retention under rainfed cropping: potential for carbon sequestration

In 1991, a long-term field experiment under rainfed conditions was started at El Batán (2240 masl; 19.31°N, 98.50°W; fine, mixed, thermic, Cumulic Haplustoll) in Mexico (Sayre et al., 2001). Treatments vary in rotation (continuous maize or wheat and the rotation of both), tillage (conventional (CT) and zero (ZT)), and crop residue management (all residue retained on the field or all residue removed from the field). After a previous soil quality assessment, percent carbon (% C: 0–5 cm and 5–20 cm) was included as a soil quality indicator in the minimum data set for future dynamic soil quality evaluation (Govaerts et al., 2006b). The % C levels in the topsoil of fields with 12 years of different tillage and residue management are compared (Table 4). Under ZT combined with residue retention on the surface, the total C sequestered in the uppermost layer (0–5 cm) was significantly higher than for CT. The net accumulation in the 20 cm top layer was up to 1.1, 1.3 and 1.4 times bigger in ZT with residue retention than in CT with residue incorporation, CT without residue incorporation, or ZT without residue retention, respectively. In both tillage systems, there was no accumulation of soil organic carbon (SOC) with residue removal, except for continuous wheat ZT with residue removal. The ZT with continuous wheat and residue removal showed similar soil organic C as ZT with residue retention. This suggests that the continuous wheat crops provided enough root material to permit an accumulation of SOC after 12 years. ZT with crop residue retention clearly resulted in higher stratification ratios between the 0–5 cm and 5–20 cm layers than CT. In the sub 5–20 cm, SOC values for ZT were half the values in the top layer. Tillage led to homogenization of the soil profile. A much smaller increase (mean value of 12% less carbon in the 5–20 cm layer for CT, keeping the residue) occurred between the 0–5 cm and 5–20 cm layer. These findings support the conclusion that ZT in combination with residue retention increases total SOC. However, increases in yield and consequently in retained biomass were rather small, especially for wheat (Govaerts et al., 2005). This is of major importance, since the rate of organic C input from plant biomass alone is not the only determining factor for C sequestration, but the combination of tillage and residue input. SOC sequestration occurs in those management systems that add high amounts of biomass to the soil, cause minimal soil disturbance, conserve soil and water, improve soil structure, enhance the activity and diversity of soil fauna, and strengthen mechanisms of elemental cycling (Lal, 2004b).

Table 4
Percentage of carbon for the different treatments in a long-term sustainability trial (El Batan, Mexico)

Tillage system	Zero-tillage		Conventional tillage	
Residue management	Retention	Removal	Retention	Removal
Overall mean (%) 0–5 cm stratum				
MM[a]	2.19 ab	1.11 f	1.45 ed	1.19 f
MW	2.26 a	1.45 ed	1.44 ed	1.26 ef
WM	2.23 ab	1.43 ed	1.47 d	1.17 f
WW	2.04 bc	1.91 c	1.42 ed	1.29 edf
Residue[b]	2.18 a	1.47 b		
Tillage[c]	2.18 a		1.44 b	
Overall mean (%) 5–20 cm stratum				
MM[a]	1.17 bcde	1.01 f	1.32 a	1.07 def
MW	1.15 bcdef	1.06 def	1.25 abc	1.14 bcdef
WM	1.10 cdef	1.05 ef	1.27 ab	1.03 ef
WW	1.13 bcdef	1.08 def	1.21 abcd	1.17 bcde
Residue[b]	1.14 a	1.05 b		
Tillage[c]	1.14 a		1.26 b	

[a] W, wheat; M, maize; second letter of rotation was crop planted during 2002 cycle; different letters indicate significant difference with LSD test at $P = 0.05$.
[b] Bulked effects of residue management in zero-tillage; different letters indicate significant difference with LSD test at $P = 0.05$.
[c] Bulked effects of tillage when residue is retained; different letters indicate significant difference with LSD test at $P = 0.05$.

The long-term trial showed the positive effects of ZT seeding systems, crop rotation, and crop residue retention over 12 years. Leaving the residue in the field is critical for ZT practices, as it improves both the chemical and physical conditions of the soil. On the contrary, where residue is removed and under ZT, we observed low total organic carbon in the 0–20 cm stratum, low aggregate stability, high accumulation of Mn, and top layer slaking. Low time-to-pond values and high runoff are the result. Soil quality in conventionally tilled plots is intermediate, as reflected particularly in the physical status of the soil (Govaerts et al., 2006b). Residue retention is less effective at increasing soil quality under CT than under ZT. Conservation agriculture (reduced/zero-tillage, crop rotation, and the retention of rational amounts of residues) increases SOC sequestration C. In addition to the environmental benefits of such practices, the improvements in soil quality help increase farming system productivity, thereby contributing to the food security of farm households (Lal, 2004b).

8. Mitigation through crop and resource management and wheat genetic enhancement

Nitrous oxide (N_2O) is a potent greenhouse gas generated through use of manure or nitrogen (N) fertilizer and susceptible to denitrification (several groups of heterotrophic bacteria use NO_3^- as a source of energy by converting it to the gaseous forms N_2, NO, and NO_2). Thus N_2O is often unavailable for crop uptake or utilization (Smith et al., 1990). In many intensive wheat-cropping systems common N fertilizer practices lead to high fluxes of N_2O and nitrous oxide (NO) (Matson et al., 1998). Reduced emissions (50% less) are possible in intensive irrigated systems without affecting wheat yields, with proper amounts and timing of N applications. Use of an optical, hand held sensor to calculate the normalized differential vegetative index (NDVI), thereby assessing yield potential as plants grow, can reduce unneeded N fertilizer inputs, saving farmers money and protecting the environment by reducing trace gas emissions.

The NDVI, which is calculated with measurements of reflected light from the red and near-infrared bands, has long been used as an indirect measure of crop yield, including that of wheat (Pinter et al., 1981). Earlier results indicated that the handheld NDVI sensor is a time-efficient tool and gives reproducible results. NDVI sensors are increasingly used in the precision agriculture for the site-specific estimation of nitrogen fertilizer requirements. The NDVI was therefore used to determine which resources were limiting under ZT with residue removal, particularly compared to ZT with crop retention (Govaerts et al., 2004). In the agro-ecological zone where the research took place, water was the limiting resource that induced specific, within-plot plant performance patterns under ZT with residue removal. Residual nitrogen was high where NDVI values were low. This indicates that enough nitrogen was present, but that it was not available to the plant, due to limited moisture. The combination of adequate agronomic practices and use of optical sensors can increase resource-use efficiency.

Keeping this nitrogen in ammonium form will influence the way nitrogen becomes available for crop uptake, improve nitrogen recovery, and minimize the nitrogen wastage which is associated with pollution and global warming (Subbarao et al., 2006). Several synthetic nitrification inhibitors (©Nitrapyrin, ©DCD, and ©Terrazole) are available as fertilizer additives (Slangen and Kerkhoff, 1984). However, except for certain niche production systems – the eastern US Corn Belt and winter wheat areas in North America – these chemical nitrification inhibitors are rarely effective for other production systems (Subbarao et al., 2006). Because of the serious limitations associated with their functionality and cost-effectiveness, these chemical nitrification inhibitors are not widely adopted by the farmers. Cost-effective chemical inhibitors that suppress nitrification in tropical and temperate production environments are urgently needed.

It has been suggested that certain tropical grasses (such as *Brachiaria humidicola*) inhibit or reduce soil nitrification by releasing inhibitory compounds from roots and suppress *Nitrosomonas* bacteria (Ishikawa et al., 2003; Subbarao et al., 2004, 2005; Wang et al., 2005). Researchers from the Japan International Center for Agricultural Sciences (JIRCAS) developed a highly sensitive bioassay system using a recombinant *Nitrosomonas europaea*, that can detect nitrification inhibition (NI activity) from root exudates or tissue extracts of small samples quickly and reliably (Iizumi et al., 1998; Subbarao et al., 2004). Some of these tools and protocols can be used to detect and quantify the nitrification inhibition capacity of plant roots (Subbarao et al., 2005; Wang et al., 2005). The concept of suppressing nitrification by releasing inhibitory compounds from plant roots is termed as biological nitrification inhibition (BNI; Subbarao et al., 2005, 2006). The bioassay system developed at JIRCAS will allow characterization plant BNI ability, opening the potential to select for and genetically enhance this capacity in major field crops like wheat.

Several wheat cultivars tested so far lacked the ability to inhibit nitrification via exudates from their roots. Recently JIRCAS researchers in collaboration with CIMMYT discovered a source for high BNI ability in *Leymus racemosus*—a wild relative of wheat (Subbarao et al., 2007). A *Leymus* chromosome containing the relevant gene(s) was introduced into wheat, and biological nitrification inhibitors were also produced and productivity increased. Further studies, however, needed to characterize and quantify the BNI ability from wild relative; when further confirmed, this will open the way for genetically improving the BNI ability of the cultivated wheat using wild relatives as a source for this trait.

9. Conclusion

New wheat cultivars are needed to adapt the crop to changing environments and meet the nutritional needs of people, particularly those in the developing world, where farmers increasingly adopt resource-conserving practices. In addition to major increases in genetic yield potential, wheat farmers will always benefit from innovative, improved crop husbandry that reduces overall costs while permitting enhanced input efficiency for irrigation water, fertilizer, and pesticides. Conservation agriculture farming practices can reduce production costs, enhance yield stability, and make crop production more sustainable. The adoption of alternative cultivars and other technology options in wheat-cropping systems that may be affected by global climate change will depend on the options' productivity, risk efficiency, and ability to meet end-user and market demands.

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