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Breeding crops for reduced-tillage management in the intensive, rice–wheat systems of South Asia

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Abstract The importance of reduced tillage in sustainable agriculture is well recognized. Reduced-tillage practices (which may or may not involve retention of crop residues) and their effects differ from those of conventional tillage in several ways: soil physical properties; shifts in host–weed competition; soil moisture availability (especially when sowing deeply or under stubble); and the emergence of pathogen populations that survive on crop residues. There may be a need for genotypes suited to special forms of mechanization (e.g. direct seeding into residues) and to agronomic conditions such as allelopathy, as well as specific issues relating to problem soils. This article examines issues and breeding targets for researchers who seek to improve crops for reduced-tillage systems. Most of the examples used pertain to wheat, but we also refer to other crops. Our primary claim is that new breeding initiatives are needed to introgress favourable traits into wheat and other crops in areas where reduced or zero-tillage is being adopted. Key traits include faster emergence, faster decomposition, and the ability to germinate when deep seeded (so that crops compete with weeds and use available moisture more efficiently). Enhancement of resistance to new pathogens and insect pests surviving on crop residues must also be given attention. In addition to focusing on new traits, breeders need to assess germplasm and breeding populations under reduced tillage. Farmer participatory approaches can also enhance the effectiveness of cultivar development and selection in environments where farmers' links with technology providers are weak. Finally, modern breeding tools may also play a substantial role in future efforts to develop adapted crop genotypes for reduced tillage.

Keywords Conservation agriculture · Reduced tillage · Zero-tillage · Wheat improvement · Wheat breeding · Participatory varietal selection

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Introduction

Reduced tillage is becoming popular among farmers around the globe. Due to the potential for enhanced productivity and cost savings, most leading agricultural institutions and governments are promoting reduced tillage. The practice is gaining popularity in rice–wheat cropping areas in South Asia (Hobbs 2001; Joshi et al. 2005), which at 14 million hectares cover around one-third of the total rice area and two-fifths of the total wheat area in India, Pakistan, Nepal, and Bangladesh, and account for some 30% of those nations' rice and wheat outputs (Hobbs and Morris 1996) and over half of the 24 million hectares of rice–wheat systems in the Asian subtropics (Ladha et al. 2000; Joshi et al. 2005). Continuous rice–wheat cropping in South Asia for several decades has led to declines in productivity and raised concerns about sustainability (Paroda et al. 1994; Hobbs and Morris 1996; Joshi et al. 2006). The recent adoption of resource-conserving practices is considered beneficial, but has also turned the attention of agricultural scientists to breeding strategies that address the new production circumstances.

Conventional tillage operations have three broad objectives: (i) to place seed in the soil, (ii) to break capillaries and aerate the soil, and (iii) to control weeds. Zero-tillage or reduced tillage does not involve these operations and presents growing plants with conditions that differ substantially from those of tilled soils, particularly where residues are retained.

How no-till is different from conventional tillage?

It has been suggested that no-till farming is more than just the elimination of ploughing; it involves developing a complete package of agro-ecologically sound management practices to fit the overall scheme of farm systems trends of specific regions (Lal et al. 2004). The concept challenges the scientific basis of ploughing as an original, universal method of soil preparation (Lal et al. 2004). From the viewpoint of plant breeding, reduced tillage and its effects differ from those of conventional tillage in many ways: (i) the micro-environment (soil structure, available moisture); (ii) the range of host–weed competition over years; (iii) the moisture regime for deep-sown seed or under stubble; (iv) different host–pathogen interactions/thresholds in the presence of stubble and other crop residues; (v) residue decomposition effects; (vi) abiotic stresses; (vii) types of mechanization (seed drills, bed planters); (viii) allelopathy effects; and (ix) crop performance in problem soils (e.g. salinity, with surface salt).

Suitable cultivars

In areas where reduced tillage is gaining popularity, farmers require cultivars adapted to the new practices (Joshi et al. 2004a, 2006). For surface seeding and zero-tillage planting, the cultivar should possess faster root development to enable rapid establishment of the crop (Trethowan and Reynolds 2005), thereby getting the seedling past an early, harsh environment and taking the best advantage of available soil moisture. The two leading abiotic stresses of wheat, heat and drought, are expected to intensify in future due to global warming and water scarcities. Much of South Asia's rice–wheat zones qualify as heat stressed, as defined by Fischer and Byerlee (1991), with mean daily temperatures above 17.5°C in the coolest month. In addressing this issue, breeders need to remain cognizant of the importance of assimilate availability during the rapid spike growth phase (Fischer 1985). Stress adaptive traits, extensive root systems, medium-tall to tall stature, and high tillering capacity, increase the potential for nutrient and water uptake, but do not necessarily increase yield (Blum 1996; Reynolds 2002).

Early studies failed to detect genotype × tillage practice interactions (Dao and Nguyen 1989; Ditsch and Grove 1991)—likely a result of the small number of genotypes tested and perhaps the fact that they were bred under conventional tillage (Trethowan and Reynolds 2005). Recently, significant genotype × tillage interaction was reported in tests involving diverse genotypes, requiring plant breeders to tailor cultivars to tillage systems (Sayre 2002; Klein 2003). In a comparison of a conventional cultivar (Janz) and a novel experimental line (Vigor 18) bred for high leaf vigour, Watt et al. (2005) found that the latter grew best in unploughed soil. They suggested faster root growth, different exudates promoting more beneficial rhizosphere microflora, or modified shoot responses as possible mechanisms for the superior growth of Vigor 18. Hence, vigorous genotypes may present an opportunity for increased productivity under reduced tillage (Watt et al. 2005). In a study at Banaras Hindu University, Varanasi, India, comparing 12 wheat lines under conventional and zero-tillage conditions for 3 years (2002–2004), cultivars PBW 443 and HD 2627 did not perform well under zero-tillage, whereas cultivars HUW 468, HUW 234, and PBW 343 performed equally well under both tillage systems (Table 1). It is worth noting that both HUW 234 and PBW 343 were developed under conventional tillage and are known in India as widely adapted and currently occupy some two and six million hectares, respectively.

The tillage × genotype interactions discussed above suggest that cultivar development should be targeted to tillage requirements. Following this approach, wheat breeders of the International Maize and Wheat Improvement Center (CIMMYT) have begun to select parental materials on the basis of performance under zero-tillage (Trethowan and Reynolds 2005). The products of this approach need to be tested in farmers' fields.

Table 1 Yield performance of 12 wheat genotypes under zero-tillage and conventional sowing in 3 years of testing

Genotype	Treatments and mean yield (kg)		Mean
	Conventional	Zero-tillage	
HUW 234	4,211.11	4,323.44	4,267.28
HUW 468	5,152.33	5,209.67	5,181.00
HUW 510	4,125.33	4,172.11	4,148.72
HUW 516	5,309.44	5,350.11	5,329.78
PBW 343	5,212.11	5,134.56	5,173.33
PBW 443	4,201.11	3,985.67	4,093.39
HD 2627	5,002.89	4,828.11	4,915.50
HD 2733	4,886.78	4,943.11	4,914.94
UP 2338	4,503.11	4,550.11	4,526.61
NW 1012	4,710.89	4,767.11	4,739.00
DBW 14	4,275.11	4,333.11	4,304.11
Raj 3765	3,943.56	3,985.11	3,964.33
Mean	4,627.81	4,631.85	

$LSD_{0.05}$ for genotype main effects—42.51, treatment main effects—NS, genotype × treatment combinations—60.12

In many regions, such as the eastern Indo-Gangetic plains of South East Asia, reduced tillage and residue retention are enabling farmers to sow wheat earlier than normal, when temperatures remain somewhat higher than the optimum 20°C. For such areas, wheat lines must possess early heat tolerance. Alternatively, mild vernalization could maintain cultivars in the vegetative growth phase when temperatures are higher. Likewise, it was observed that short-duration wheat cultivars performed poorly (drastically reduced tillering and biomass accumulation) if sown early. This is not the case with cultivars like PBW 343, considered late-maturing in the eastern Indo-Gangetic plains. Hence, there is need to produce cultivars with higher biomass and high grain yields, given the same nutrient input. This genetic improvement must come through both photosynthetic assimilation capacity and by partitioning of assimilates to promote high grain number and growth rate (Richards 1996; Reynolds et al. 2001). Another way to increase grain number in wheat will be to breed for multi-ovary florets with up to six kernels per flower (Chen et al. 1998), taking due care that this does not lead to very small grains.

As indicated above, physiological selection traits may also improve genetic yield potential in wheat. A study in a high-yielding environment in Mexico revealed that leaf photosynthetic rate, leaf conductance, and canopy temperature depression (CTD) were associated with yield gains in eight spring wheat lines, representing progress in yield potential between 1962 and 1988 (Fischer et al. 1998). These issues are equally relevant under reduced-tillage environments. In addition, physiological traits, including CTD, were strongly associated with performance in yield trials at a number of warmer wheat-growing locations worldwide (Reynolds et al. 1994). Physiologically selected traits for drought tolerance have been incorporated into a number of Australian wheat breeding programs, including higher transpiration efficiency, greater early vigour, and reduced tillering (Richards et al. 1996). Leaf traits such as erect leaf posture could also be useful under some conditions. Work at CIMMYT with near isogenic lines of spring wheat showed that erect leaves were associated with higher grain number and increased transpiration (Araus et al. 1993). This trait was shown to reduce diseases such as spot blotch in South Asia (Joshi and Chand 2002) and reported to be useful under moisture stress (Innes and Blackwell 1983). In view of its importance, erect leaf was introgressed into the wheat germplasm base, and is present in some of CIMMYT's highest-yielding durum and common wheat lines (Fischer 1996).

Soil factors

The roots are the first and most important organ that nourishes the plant, but has been neglected by many plant breeders (Bais et al. 2001; Manske et al. 2001). In reduced tillage, soils may initially be more compact and unfavourable for root growth. Reduced root growth in high-strength soils may be partly responsible for patchy growth and losses in yield of direct-drilled wheat with surface straw retained (Cornish and Lymbery 1987; Kirkegaard et al. 1994). Plant breeders can address this issue by developing cultivars with increased root mass, able to handle soil physical resistance and harvest nutrients from deeper profiles. In a study at Banaras Hindu University, root biomass was measured in pot experiments for 12 wheat lines (Table 2). The plastic pots (60 cm height × 30 cm diameter) were filled with 8 kg soil medium of two types (7.5:2:0.5 and 5:3:2 mixture of sand:silt:clay) to assess differences among genotypes under diverse growing media. Two cultivars (PBW 443 and HD 2627) that did not yield well under zero-tillage possessed significantly lower root biomass, whereas HUW 234, the most popular cultivar of the Northeastern Plains Zone of India, had a high root biomass (Table 2). Other cultivars showed similar root biomasses in the pot experiments.

In reduced tillage, soil is less disturbed; it is thus suggested that soil–root contact is improved and more suitable for the release of root exudates (organic acids, carbohydrates, amino acids, enzymes, alkaloids, flavonoids, steroids, and terpenoids) that promote rhizosphere microflora and can help protect the roots from pathogens (Hocking 2001). There is a need to investigate lines and cultivars for this trait.

Table 2 Root biomass of 12 wheat genotypes under zero-tillage and conventional sowing in 3 years of testing

Genotype	Treatments and mean root biomass (g)		Mean
	Sand:silt:clay (7.5:2:0.5)	Sand:silt:clay (6:3:1)	
HUW 234	3.16	3.31	3.24
HUW 468	3.41	3.46	3.44
HUW 510	2.85	2.93	2.89
HUW 516	3.62	3.54	3.58
PBW 343	3.47	3.39	3.43
PBW 443	2.86	2.68	2.77
HD 2627	3.30	3.02	3.16
HD 2733	3.35	3.30	3.33
UP 2338	3.11	3.01	3.06
NW 1012	3.22	3.18	3.20
DBW 14	2.94	2.94	2.94
Raj 3765	2.98	2.83	2.90
Mean	3.19	3.13	

LSD$_{0.05}$ for genotype main effects—0.08, treatment main effects—0.03, genotype × treatment combinations—0.11

Water requirements

Crops are often grown in environments where water is a limiting factor, water use efficiency and reduction in soil evaporation are important considerations. Any increase in early seedling vigour should reduce evaporative losses (Richards 1992). If the crop duration is short, greater vigour is likely to increase final biomass and yield and may be an effective way to reduce weed growth. The available information on the variation and genetics of seedling emergence for wheat (Singh et al. 1998a) and oats (Radford and Key 1993) can be exploited for such purposes.

Among traits that contribute to increased seedling vigour, coleoptile length is the most important (Fick and Qualset 1976; Whan 1976). Short coleoptiles result in poor emergence, leading to poor crop establishment. In dry environments, farmers sowing into a declining moisture profile following rainfall often sow at greater depth (8–12 cm) to ensure seed contact with moisture (Paulsen 1987). Better emergence is achieved by sowing wheat with long coleoptiles.

The presence of dwarfing genes is associated with a significant reduction in coleoptile length (Allan et al. 1962; Feather et al. 1968; Fick and Qualset 1976) and poor emergence under deep sowing or stubble (Richards et al. 2001). Allan (1980) suggested that the accumulation of modifier genes which favour emergence could be important in breeding for better-emerging semi-dwarf wheat cultivars. Increased coleoptile length can be achieved by selecting within semi-dwarf germplasm (Beharev et al. 1998), but greater progress can be made using parents that are sensitive to gibberellic acid (GA), although short stature also needs to be sought (Rebetzke et al. 1999). Wheat cultivars and lines with long coleoptiles also tend to have large early leaves and more rapid rates of emergence, which together contribute to faster leaf area development (Richards et al. 2001). Trethowan et al. (2001) suggested the possibility of selecting within families carrying *Rht1* and *Rht2* dwarfing genes for potentially longer coleoptiles; they also suggested that wheat breeders should be able to select short stature, non-*Rht1* or non-*Rht2* hexaploid wheats (for example, those bred from Seri 82 and Culiacan 89) with better emergence characteristics, for environments where deep sowing into stored soil moisture is practiced.

Host–pathogen interactions

Despite the fact that surface residues constitute a principal source of inoculum, reduced tillage with residue retention has increased significantly throughout North America (Anonymous 1995) and many other countries. The effects of tillage on the development and severity of crop diseases vary, depending on the disease, type of tillage system, and the effectiveness of other disease management practices (Felton et al. 1978) (Table 3). Of particular concern are crop diseases favoured by cool and wet soils. The most troublesome diseases in high-residue systems are *Fusarium* head blight (Bai and Shaner 1994; Dill-Macky and Jones 2000) and tan spot (caused by *Pyrenphora tritici repentis*) (Trethowan and Reynolds 2005). On the other hand, increases in soil organic matter may favour friendly fungi such as *Trichoderma* (Harman et al. 2004).

Table 3 Effect of crop residues on the growth and reproduction of pathogens of different crops grown in rice–wheat cropping areas of India

Disease	Pathogen and its nature	Host range	Incidence	Spatial variability	Temporal variability	Effect of crop residue
Soil borne (seedling diseases, collar rot, damping off)	Facultative parasites: *Phythium*, *Phytopthora, Rhizoctonia*, *Scelerotium, Macrophomina*	Broad	Locally high	Very high depending on scale and habitat	Periodic cycles of disease	May promote disease up to 15 November in Eastern Indo-Gangetic plains
Wilt	Facultative saprophyte:		High	Depends on scale and habitat	Periodic cycles of disease	Survive on host residue for 2–4 years. No multiplication on other crop residues
	Fusarium udam	Pigeon pea				
	Fusarium oxysporum fsp. *Ciceri*	Chick pea				
	F. oxysporum fsp. *pisi*	Pea				
	F. oxysporum fsp. *lini*	Lentil				
Necrotroph (foliar diseases)	Facultative saprophyte	Restricted, except sheath blight pathogen of rice	Very high	Very high depending on the scale and habitat	Periodic cycles of disease	Survival not detected on residues of wheat and paddy. All pathogens survive on the residues for limited periods. Most pathogens are host specific, and do not infect other hosts
Sheath blight of rice	*Rhizoctonia solani*					
Bacterial blight of rice	*Xanthomonas oryzae* pv. *oryzae*					
Spot blotch of wheat and barley	*Bipolaris sorokiniana*					

Pathogens that survive and multiply on crop residues may be promoted by reduced tillage. However, not all pathogens have broad host ranges nor survive on all types of crop residue. For example, *Fusarium* pathogens of pulses survive on residues of host crops, but not on rice or wheat. Spot blotch caused by *Bipolaris sorokiniana*, considered the most important disease of wheat in the eastern Indo-Gangetic Plains of India (Joshi et al. 2002, 2004b, c; Pandey et al. 2005), did not increase during a recent 3-year (2001–2004) survey of 172 farm fields growing cultivar HUW 234 across 39 villages in Varanasi, Mirzapur, and Chandouli Districts of eastern Uttar Pradesh (Table 4). This is a zone where zero-tillage of wheat is gaining momentum and covered about 100,000 ha in 2005. However, given the ability of pathogens to evolve rapidly, breeding programs must continually strengthen resistance levels in germplasm using suitable resistance sources. In this regard, a simple morpho-physiological marker can be helpful. One example is leaf tip necrosis associated with resistance to spot blotch (Joshi et al. 2004b) and genes *Lr34* and *Yr18* involved in slow rusting resistance to leaf rust (*Puccinia triticina*) and stripe rust (*Puccinia striiformis*), respectively (Dyck 1991; McIntosh 1992; Singh 1992a, b). In addition to disease incidence, reduced tillage may have effects on insect pests. Deep ploughing in summer kills many over-wintering insects by exposing them to high temperatures and birds. This does not happen in reduced tillage and may favour insect pests such as shoot borers (*Sesamia inferens* and *Scirpophaga incertulus*) in paddy.

Residue decomposition as a genetic trait

Crop residues are a tremendous natural resource (Kumar and Goh 2000). Decomposition of retained residues is influenced primarily by the environment and management factors (Parr and Papendick 1978; Tanaka 1986) and to a minor extent by the species (Smith and Peckenpaugh 1986) and cultivar type (Summerell and Burgess 1989). Several workers reported differences in residue decomposition due to differences in N, C/N, lignin/N, and polyphenol/N ratios, even for the same species (Kumar and Goh 2000). Summerell and Burgess (1989) reported cultivar differences in the decomposition of wheat and barley straw, suggesting a potential for selection of cultivars with variable decomposition rates. Faster residue decomposition is preferred for most environments. However, in some warm wet situations, a slower rate of decomposition may be needed to maintain soil cover for a longer period. More studies are required to identify variation among genotypes under reduced tillage and residue retention.

Ecological and environmental factors

Heavy crop residues could allow less sunshine for emerging seedlings leading to greater retardation in growth compared with conventional tillage.

Table 4 Comparison of area under disease progress curve (AUDPC) and mean severity (%) of spot blotch in 172 fields of cultivar HUW 234 grown under zero-tillage and conventional sowings in 3 years of testing in eastern Uttar Pradesh, India

Year	District	No. of fields	AUDPC				Mean severity (%)	
			Conventional	Zero-tillage	$LSD_{0.05}$	Conventional	Zero-tillage	$LSD_{0.05}$
2001–2002	Varanasi	7	1,349.29	1,237.86	NS	61.43	57.50	NS
2002–2003	Varanasi	11	1,174.09	1,135.00	NS	53.64	51.82	NS
2003–2004	Varanasi	14	1,353.21	1,057.14	205.8	62.86	53.57	7.99
2001–2002	Mirzapur	22	1,351.82	1,143.18	NS	61.36	55.45	NS
2002–2003	Mirzapur	24	1,185.21	1,023.13	141.7	55.42	50.00	NS
2003–2004	Mirzapur	33	1,189.55	1,175.30	NS	57.27	55.45	NS
2001–2002	Chandouli	12	1,209.58	1,092.08	NS	55.83	51.67	NS
2002–2003	Chandouli	21	1,461.67	1,253.81	182.3	63.81	57.62	6.01
2003–2004	Chandouli	28	1,340.36	1,316.61	NS	60.00	60.36	NS
Mean			1,289.01	1,267.09	NS	59.19	55.12	2.37

NS non-significant

Reduced tillage also affects soil temperatures (Unger and McCalla 1980), resulting in a cooler field in summer (Hatfield and Prueger 1996). Indirectly, this may benefit early sowing (October or early November) of wheat in the Indo-Gangetic Plains or in environments where optimal temperatures occur in the second half of November. It may also be beneficial for summer crops such as urd (*Vigna mungo*) and mungbean (*Vigna radiata*) in population-dense regions of South Asia, where cropping intensity needs to be increased for food security. Hence, cultivars that germinate well and produce vigorous seedlings under lower temperatures are desirable.

Crop residues create phytotoxic conditions for some crops (Cochrane et al. 1977; Lynch 1978). Under anaerobic conditions phtyotoxic compounds (e.g. acetic acid and butyric acid) impair germination (McCalla and Haskins 1964; Guenzi and McCalla 1966; Rao and Mikkelson 1977; Wallace and Elliott 1979). This phytotoxicity is reported within as well as between crops. Therefore, seedling traits associated with resistance in to organic acids may also be targeted when improving crops for reduced-tillage/residue retention systems.

Agronomic requirements

Tillage is widely used to control weeds directly and by burying their seeds. Germination of many weed seeds is stimulated by exposure to light. In the presence of crop residues, only those weeds that can grow under diffuse light would flourish. Hence, changes in weed populations, at both the species and temporal levels, may occur under reduced tillage. As mentioned above, cultivars with faster emergence or displaying better competition are more desirable in both conventional and reduced/zero-tillage systems. However, they appear to be of greater importance in situations with more weeds and where tillage is not used for weed control. The yield performance of 12 diverse wheat lines grown under zero-tillage and conventional sowing with weed-managed and non-managed conditions for 3 years at Banaras Hindu University, Varanasi, is given in Table 5. In the weed-managed trial, both hand and chemical (2,4-D and isoproturon) weeding were

Table 5 Mean yield of 12 wheat lines in 3 years of testing (2002–2004) under weed-managed (WM) and non-managed conditions in conventional and zero-tillage plantings

Genotype	Conventional sowing			Zero-tillage sowing			% Yield loss		
	Weed managed	Non-weed managed	Mean	Weed managed	Non-weed managed	Mean	Conventional sowing	Zero-tillage sowing	Mean
HUW 234	4,503.33	3,493.11	3,998.22	4,608.33	3,379.89	3,994.11	22.43	26.66	24.55
HUW 468	5,457.00	3,734.44	4,595.72	5,486.89	3,829.56	4,658.23	31.57	30.21	30.89
HUW 510	4,418.00	3,270.11	3,844.06	4,508.44	3,116.44	3,812.44	25.98	30.88	28.43
HUW 516	5,614.33	3,916.44	4,765.39	5,666.00	3,886.44	4,776.22	30.24	31.41	30.83
PBW 343	5,504.33	3,589.67	4,547.00	5,408.89	3,575.56	4,492.23	34.78	33.89	34.34
PBW 443	4,511.89	3,034.44	3,773.17	4,002.67	2,811.89	3,407.28	32.75	29.75	31.25
HD 2627	5,308.67	3,418.44	4,363.56	4,901.11	3,280.33	4,090.72	35.61	33.07	34.34
HD 2733	5,160.33	3,360.33	4,260.33	5,304.67	3,325.56	4,315.12	34.88	37.31	36.10
UP 2338	4,795.33	3,328.33	4,061.83	4,911.67	3,325.78	4,118.73	30.59	32.29	31.44
NW 1012	4,984.67	3,317.33	4,151.00	5,128.67	3,461.33	4,295.00	33.45	32.51	32.98
DB W14	4,545.33	3,333.56	3,939.45	4,694.67	3,201.56	3,948.12	26.66	31.80	29.23
Raj 3765	4,246.67	3,248.11	3,747.39	4,368.11	3,230.33	3,799.22	23.51	26.05	24.78
Mean	4,920.82	3,420.36	4,170.59	4,915.84	3,368.72	4,142.28	30.20	31.32	30.76

$LSD_{0.05}$, WM main effects—53.55, WM main effects—64.38, treat. main effects—0.88; $LSD_{0.05}$, genotype main effects—131.18, genotype main effects—52.56, genotype main effects—2.15; $LSD_{0.05}$, WM × genotype combinations—185.51, WM × genotype combinations—181.10, treat × genotype combinations—3.05

applied to keep the field almost free from weeds. In the non-managed trial, no weed control was used. Faster-growing lines, such as HUW 234 and Raj 3765, gave about 25% less yield in the presence of weeds, whereas the slow-growing line PBW 343 had a decline of about 35% (Table 5).

In the Indo-Gangetic Plains, zero-tillage has been highly beneficial in controlling *Phalaris minor*. However, in some cases, crop canopies at early growth stages may become restricted, so more weeds may be expected per unit area than in a ploughed field. For such situations (which may also occur under conventional tillage), genotypes with greater early vigour, or those exhibiting favourable allelopathy, may be selected (White et al. 1989; Weston 1996). Variation for early vigour was reported in wheat (Singh et al. 1998a; Richards and Lukacs 2001) and oats (Radford and Key 1993), and further improvement could be obtained by understanding and utilizing factors that contribute to greater vigour in barley (Richards et al. 2002). Several studies show that some crop cultivars are allelopathic and that their inhibitory effects on weeds apply under field conditions (Olofsdotter et al. 1999; Fujii 1993; Wu et al. 1999). For example, residues of rye and other small grain crops inhibit weed emergence and growth (Shilling et al. 1986), likely due to phytotoxic effects (Kumar and Goh 2000). There has been substantial recent progress toward identifying chemicals responsible for weed suppression (Rimando et al. 2001; Kato-Noguchi and Ino 2003; Wu et al. 2000) and understanding the genetics underlying allelopathy in rice (Olofsdotter et al. 1995; Jensen et al. 2001; Ebana et al. 2001) and wheat (Wu et al. 2003).

Mechanization issues

The sowing depth of seeds may vary under reduced tillage. In surface seeding, seeds are dispersed on the soil surface, whereas machine planting into crop residues may place seed at a lower depth than recommended. Hence, cultivars displaying better germination and growth under shallow or surface seeding would be more desirable. However, in drier conditions, the surface soil has increased mechanical impedance, which may affect seedling emergence (Benoit and Kiskham 1963). Banley et al. (1965) showed that a reduction in soil mechanical resistance increases the probability of root penetration.

The presence of mulch in the topsoil keeps it wetter; in most situations this is beneficial for seedling germination and growth. The Star (Punch) Planter, which penetrates surface mulch, works well for crops like rice, pulses, and maize, but can result in poor establishment of wheat, which performs better when drill-sown. This suggests a need to either modify the planter to deliver appropriate amounts of seed, or develop cultivars with many fertile tillers. The variability available in synthetic wheat lines may be utilized to develop such cultivars (Mujeeb-Kazi et al. 1996).

Problem soils

As human populations increase, problem soils in more marginal or unfavourable cropping areas are being brought into cultivation. Many may be hilly and subject to stresses such as high pH, micronutrient deficiencies, or high or low moisture. The cost savings of reduced tillage are expected to drive its adoption in such settings. Zero-tilled crops perform better than conventionally tilled crops in saline soils in the eastern Indo-Gangetic Plains, but this may not be true for alkaline soils. Breeding cultivars tolerant to saline soils will continue to be an important target.

For direct seeded rice, farmers need cultivars that do not suffer from iron chlorosis or Zn or P deficiencies and which can germinate when deep seeded in moist soils. Genetic diversity in responses of wheat to deficient levels of soil micronutrients has been reported (Graham 1984, 1987, 1988a, b; Rerkase and Jamjod 1997). Variation and inheritance of such traits, or sets of traits, were investigated in soybean (Weiss 1943; Fehr 1982; Saxena and Chandel 1992), tomato (Epstein 1972), celery (Epstein 1972), rye (Graham 1984), wheat (Majumdar et al. 1990; Rengel 1992; Graham et al. 1992; Khabaz-Saberi et al. 1998; Cakmak et al. 2000), and barley (Graham 1988b; Genc 2003). Such information must be utilized for evaluation and introgression of favourable genes in crops under reduced tillage where deep sowing is the only alternative for profitable production.

Breeding approaches

Nearly all crop cultivars now grown under reduced tillage were selected in conventionally tilled environments. Various reports suggest differences in the performance of cultivars in tilled and untilled soils (Brakke et al. 1983; Newhouse and Crosbie 1987; Triplett 1986). Kronstad et al. (1978) suggested that to develop cultivars with improved performance in reduced-tillage systems, the following should be considered: (i) growth factors influenced by tillage need to be identified; (ii) genetic variability for growth factors affected by tillage must be large enough to provide sufficient scope for selection; (iii) selection criteria to identify superior lines in segregating populations must be established; and (iv) progeny with improved characteristics for reduced tillage must possess all other desirable agronomic traits for an adapted and competitive cultivar. Francis (1991) outlined the dimensions of future cropping systems based on current trends and suggested that, for a reduced-tillage system having greater amounts of crop residues, possible plant breeding solutions would be to incorporate increased seedling vigour, early stress (cold) tolerance, and tolerance to eco-fallow/zero-tillage planting.

Among the approaches to breed crops for reduced or zero-tillage, the simplest would be to grow segregating populations from crosses involving parents that adapt well under zero-tillage and incorporate useful traits (better emergence characteristics, profuse tillering, and resistance to diseases common under zero-tillage) from other parents. The genetic variation created by such crossing, growing large populations of segregating generations, and selecting plants that combine desirable traits, should lead to the development of superior genotypes. However, for proper identification of segregants suitable for reduced tillage/residue retention, segregating generations need to be grown under the targeted practice. Selection under reduced-tillage conditions is practical since it does not carry associated disadvantages.

There is need to carefully assess profitability, before establishing a long-term breeding program for new environments such as zero- or reduced-tillage systems (Francis 1990). Witcombe and Virk (2001) emphasized a low-cross-number strategy for inbreeding crops like wheat and rice, suggesting that a good approach would be to select and produce large segregating populations, thereby increasing the probability of recovering superior genotypes. Singh et al. (1998b) investigated the type of cross and selection scheme (pedigree, modified bulk, selected bulk, and non-selected bulk) in wheat and found few differences among schemes for grain yield or other traits. Although the four selection schemes did not show significant differences, the selected bulk scheme resulted in a larger number of advanced lines at a relatively low cost. Using simulation studies, Wang et al. (2003) showed that the selected bulk approach gave slightly better genetic gains than other selection schemes. Sowing segregating populations derived from selected bulks also appears attractive for zero-tillage plantings, because a large number of plants can be sown and allowed to compete among themselves as populations. It is also advisable to grow selected bulk segregating populations in conventional and zero-tillage in alternating generations to ensure that the resulting genotypes can be grown under both systems.

Among various methods, the single-backcross approach has been suggested as very effective in shifting a greater proportion of progenies in the segregating generations towards higher mean values, thereby enhancing the chance of getting superior lines (Singh and Huerta-Espino 2004). Following this approach, Singh et al. (2000) developed derivatives of the two most popular cultivars, PBW343 and Inqualab 91, in South Asia that not only carried high levels of oligogenic adult-plant, durable resistance to leaf rust and stripe rust, but also had superior grain yield potential. Using this approach, improvement of a desired trait should be possible without sacrificing other characteristics. Likewise, it was also possible to tailor superior genotypes for reduced-tillage conditions of rice–wheat cropping systems by focusing on the traits necessary for good performance. Two early-maturing lines, Inqualab 91*2/Kukuna and Attila*2/Star/4/Sonoita/Trap#1/3/

Kauz*2/Trap//Kauz—improved versions of the widely grown cultivars Inqualab 91 and Attila—produced by the methodology described above had grain yields 15–20% above the best local check, HUW 234, when tested under zero-tillage conditions at six locations of eastern Gangetic plains during 2005–2006, as well as similar superiority under conventional tillage at Banaras Hindu University, Varanasi (Fig. 1). Inqualab 91 is early-maturing, whereas Attila matures late in eastern India, but both have performed well under zero-tillage. Hence, a single-backcross program produced one line with increased yield potential and another that is significantly earlier, but with similar yield potential. These results indicate that the single-backcross breeding approach is applicable to the development of lines with high yield under zero-tillage.

Several studies suggest new physiological tools can complement conventional wheat breeding programs (Fischer et al. 1998; Reynolds et al. 1998), helping to select important traits which are difficult to quantify in breeding materials and to target highly heritable traits that limit yield (Richards et al. 2002). The successful Veery lines produced in the early 1980s (Rajaram et al. 1990) resulted from a cross of a winter wheat parent containing a 1RS chromosome (1B/1R translocation from cereal rye). These Veery lines had outstanding yield potential and other physiological characteristics. One of them, ‘Seri 82’, was shown to have superior leaf photosynthetic rate, stomatal conductance, and leaf greenness relative to a set of hallmark cultivars developed both before and after its release (Fischer et al. 1998). Through proper application of physiological criteria, selection for useful traits may be practiced in early segregating generations and in smaller populations, thereby reducing costs (Richards et al. 2002).

Modern genetic enhancement

Molecular tools, derived with increasing knowledge about the molecular and genomic bases of agronomic traits, can be applied to develop improved cultivars that enable producers to increase yields and quality, while reducing chemical inputs and production costs. The complete gene sequences of rice and *Arabidopsis* are known and our understanding of wheat and other crop genomes is improving (Varshney et al. 2005). This has facilitated the development of molecular markers for agronomic traits, particularly including simple sequence repeats (Röder et al. 1998), single-nucleotide polymorphisms (SNP) (Rafalski 2002), and conserved orthologous sets of markers (Rudd et al. 2005). The most important use of markers is for indirect selection of linked traits.

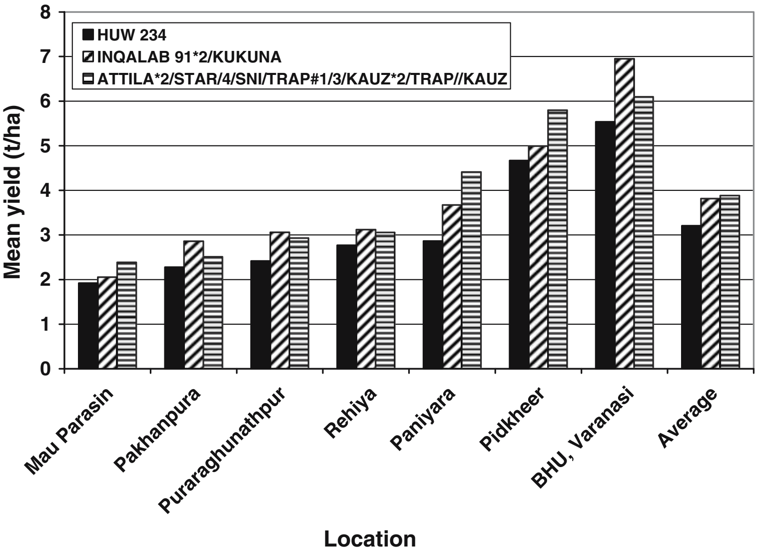


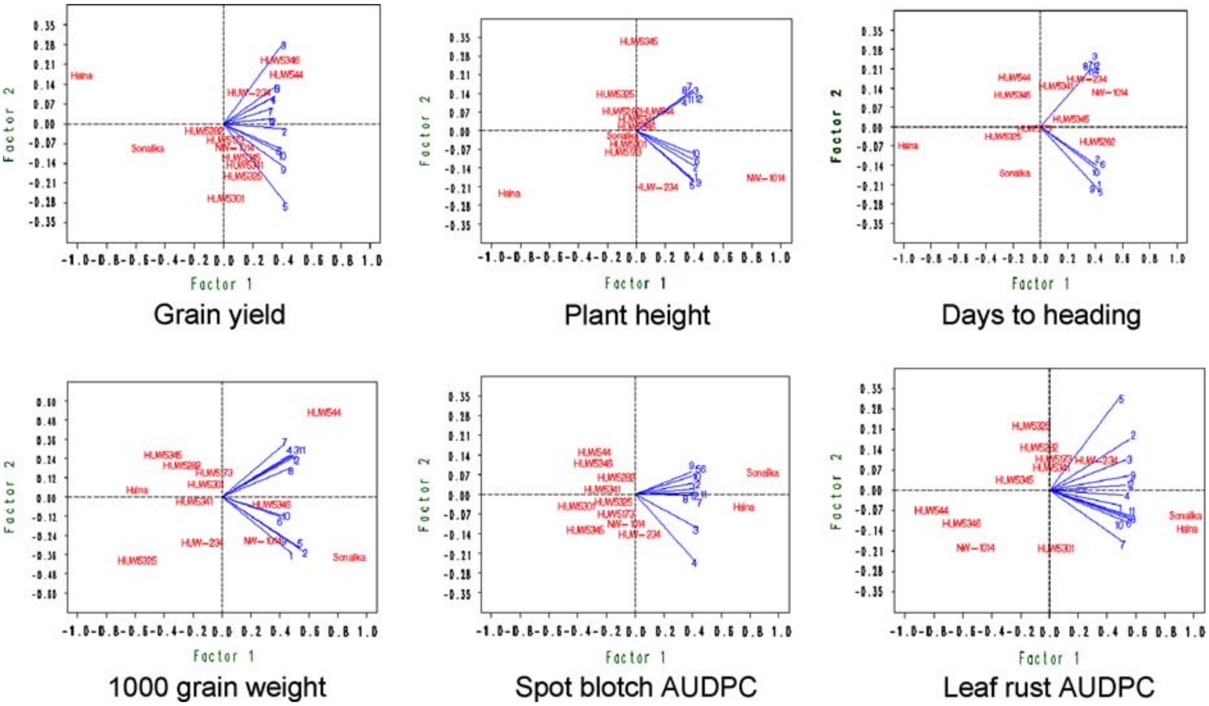
Fig. 1 Performance of two CIMMYT-derived lines compared with local check HUW 234 under zero-tillage sowing at six locations and conventional sowing at one location (BHU, Varanasi) of the eastern Gangetic Plains, 2005–2006

Over 5,000 expressed sequence tags are available for more than 50 plant species (Rudd et al. 2005). In wheat, many microsatellites (Röder et al. 1998; Pestova et al. 2000; Gupta et al. 2002; Somers et al. 2004; Rudd et al. 2005) are publicly available and used for gene tagging, mapping, and phylogenetic studies. The current level of genome coverage provided by microsatellite markers in wheat (ca. one every 10–15 cM) is considered sufficient for genetic diversity studies (Huang et al. 2002) and for locating resistance genes. Koebner and Summers (2003) suggested that the current targets of molecular marker development for wheat breeding were resistance to *Fusarium* head blight, rusts, and viral diseases, and some of such genes have been mapped in wheat (McIntosh et al. 2005) for future breeding programs. Two quantitative trait loci (QTL) on chromosome 2B associated with seedling allelopathy in wheat against annual ryegrass (*Lolium rigidum*; Wu et al. 2003) were identified by their association with restriction fragment length polymorphisms, amplified fragment length polymorphisms, and microsatellites (SSR). Markers for resistance to *Fusarium* head blight and tan spot or seedling allelopathy would be of great use in developing cultivars for reduced-tillage environments. Markers for height genes other than GA-insensitive *Rht1* and *Rht2* (Ellis et al. 2005) are also expected to play a significant role in improving coleoptile length, a trait necessary for better seedling emergence.

In the development of molecular markers for rice improvement, four main-effect QTL located on three chromosomes were identified for allelopathy with weeds; the regions collectively accounted for 35% of the total phenotypic variation for the trait in the population studied (Jensen et al. 2001). The bacterial blight resistance gene *Xa21* (Chen et al. 2000) was backcrossed into rice cultivars in China and India, as well as into elite IRRI lines (Chen et al. 2000; Sanchez et al. 2000; Singh et al. 2001). As added protection for this resistance, genes such as *xa5* and *Xa13* were combined with *Xa21* using marker-assisted selection (MAS; Sanchez et al. 2000; Singh et al. 2001). Bacterial blight resistance was incorporated into hybrid rice using MAS (Chen et al. 2000; Cao et al. 2003). Recently, Hayashi et al. (2005) developed PCR-based SNP for rice blast resistance genes at the *Piz* locus, and stressed the utility of SNP and small insertion/deletion polymorphisms (InDels) as DNA markers for genetic analysis and breeding of rice.

Markers for genes conferring resistance to cereal cyst nematode, root lesion nematode, crown rot, and tolerance to boron are now used routinely at CIMMYT (Trethowan and Reynolds 2005). Advanced CIMMYT lines with improved root health developed using MAS have been distributed globally in the Semi-arid Wheat Screening Nursery (Trethowan and Reynolds 2005). Likewise, somaclonal variation was used to breed new, high-yielding, early-maturing wheat lines with resistance to spot blotch under conventional tillage (Arun et al. 2003). Somaclones of HUW 234, the most widely grown wheat cultivar in the Northeastern Plains of India, were assessed at two sowing dates during 2001–2004 under conventional and zero-tillage at Banaras Hindu University. Stability analysis (Crossa et al. 2002) confirmed the superior performance of two variants (HUW 234-5-44 and HUW 234-5-346) (Fig. 2).

Useful knowledge about traits of potential relevance in improving wheat for conservation agriculture is expected to come from plant model systems, coupled with genomics research in *Arabidopsis* and comparative cereal genomics studies. ‘‘Tilling’’ (used here in the genetics sense) for functional analysis, is a well-established technique in barley (Caldwell et al. 2004) and is being developed for wheat (Slade et al. 2005). Wheat genes have significant homologies with 350 *Arabidopsis thaliana* genes; at least 25 of these are known to be essential for seed development in *Arabidopsis* (Drea et al. 2005). Attempts are being made to introduce the *Arabidopsis DIR-1* gene into wheat, rice, and other crops in order to increase defense against fungal pathogens (Moffat 2000). Detailed studies have also led to the discovery of promoter regulatory elements, like the dehydration responsive element (DRE) or ABA-responsive element, involved in both dehydration and low temperature-induced gene expression in *Arabidopsis* (Shinozaki and Yamaguchi-Shinozaki 1997), as well as identification of several key transcriptional factors with



Grain yield

Plant height

Days to heading

1000 grain weight

Spot blotch AUDPC

Leaf rust AUDPC

Fig. 2 Stability analysis for six traits using the Site Regression Model involving eight somaclone variants (R_5) and four check cultivars (HUW 234, Sonalika, NW 1014, and Halna) tested for two planting dates over 3 years in conventional and zero-tillage sowings. Two variants (HUW 234-5-44 and HUW 234-5-346) proved superior to parent HUW 234. *Note*. For somaclonal variants of HUW 234 abbreviated names were used as follows—HUW5173 = HUW 234-5-173; HUW5282 = HUW 234-5-282; HUW5301 = HUW 234-5-301; HUW5325 = HUW 234-5-325; HUW5341 = HUW234-5-341; HUW5345 = HUW 234-5-345; HUW5346 = HUW 234-5-346; HUW544 = HUW 234-5-44

which they interact (Liu et al. 1998). Using information from *Arabidopsis*, a comparative study on the *DREB* gene was carried out in maize (Buuren et al. 2002). Transformation of durum and common wheats using the *Arabidopsis DREB* gene improved water stress tolerance (Pellegrineschi et al. 2002a, b). This kind of work should eventually benefit crop improvement programs, including research for rice–wheat cropping under reduced tillage.

Farmer participatory varietal selection

Genetic enhancement has heretofore employed standard hybridization, segregation, and whole plant selection primarily on research stations. Participatory varietal selection (PVS) provides a way to capture information about the performance of experimental cultivars under actual farm conditions and farmer management, as well as obtaining a better appreciation of the traits and genotypes valued by farmers (Witcombe et al. 1996, 2001; Ortiz Ferrara et al. 2001; Joshi et al. 2005). Through PVS, farmers in the eastern Indo-Gangetic plains selected more profitable cultivars (Ortiz Ferrara et al. 2001). New wheat lines from CIMMYT and national research centres are being tested by farmers in the region under zero-tillage using PVS. This also appears to be a more reliable and faster way to disseminate new wheat cultivars. Of new cultivars made available to farmers, relatively few become adopted. In this direction, use of the single-backcross approach for targeted improvement of popular genotypes favours the conservative attitudes of farmers. However, widely adapted cultivars occupying large areas often become vulnerable to rust diseases. Incorporating durable resistance into such cultivars will help prevent major epidemics, while allowing farmers to continue with chosen cultivars that perform well under reduced or conventional tillage.

Conclusion

With the increasing adoption of resource-conserving practices like reduced tillage in the Indo-Gangetic Plains and elsewhere, crop breeding programs need to focus on developing cultivars that fit the new practices. Traits for this purpose should be included among breeding objectives for developing cultivars that enhance the profitability and sustainability of agro-ecosystems.

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