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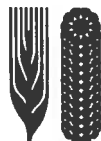
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CIMMYT

Increasing Wheat Yields Sustainably through Agronomic Means

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Abstract: This paper examines common factors that constrain wheat yields: insufficient nutrients (using nitrogen as an example); problems of late planting and poor crop establishment; suboptimal water management; lodging; and weeds. The authors suggest agronomic practices, including tillage practices, rotations, and input management options that can ameliorate important constraints and sustainably improve yields. Examples are drawn largely from rice-wheat systems in the Indo-Gangetic Plains and from wheat systems in northwestern Mexico. These examples indicate that there is still considerable potential for raising wheat yields in a sustainable manner and meeting rapidly expanding demand for wheat in developing countries.

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1. Introduction

The purpose of this study is to investigate the effects of various factors on the performance of a system. The system under study is a complex one, and its performance is influenced by many different factors. The factors that are being studied are: (1) the type of input data, (2) the type of output data, (3) the type of processing algorithm, (4) the type of hardware, and (5) the type of software. The results of the study will be presented in a series of tables and graphs. The first table shows the results of the experiments for each of the five factors. The second table shows the results of the experiments for each of the five factors, but with the results for each factor averaged together. The third table shows the results of the experiments for each of the five factors, but with the results for each factor weighted according to its importance. The fourth table shows the results of the experiments for each of the five factors, but with the results for each factor weighted according to its importance and the results for each factor averaged together. The fifth table shows the results of the experiments for each of the five factors, but with the results for each factor weighted according to its importance and the results for each factor averaged together, and the results for each factor weighted according to its importance and the results for each factor averaged together.

Increasing Wheat Yields Sustainably through Agronomic Means

P.R. Hobbs, K.D. Sayre and J.I. Ortiz-Monasterio

Introduction

Despite the impressive advances that have been made over the years in improving the yields of food crops, including wheat, there is little reason to become complacent about the food supply, especially in the developing world. During the next three decades, the population of developing countries will grow by at least 1.6%. As this growing population becomes increasingly urban-based, as incomes rise, and as consumers substitute out of rice and coarse grain cereals, the demand for wheat will rise. By 2020, two-thirds of the world's wheat consumption will occur in developing countries (CIMMYT 1997). To meet demand across the Asian Subcontinent, we will have to maintain wheat yield growth at 2.5% per year over the next 30 years, because cropped area is expected to remain minimal or even negative (Hobbs and Morris 1996). Yields will not only have to grow; they will have to grow without depleting the natural resource base on which agriculture depends.

This is no small challenge for agricultural research, but there are reasons to be optimistic that researchers will be able to develop technologies that can improve wheat yields and at the same time preserve the resource base. Some of the most exciting opportunities for sustainably improving wheat system productivity have been developed through crop management research, and they are reviewed in this paper. We begin by describing the gap between farmers' actual yields and potential yields and the reasons for that yield gap. Next, we review a series of factors that

influence yields: nutrients, planting date, crop establishment, water management, lodging, and weed control. We provide examples of how agronomic practices can improve the efficiency of each factor and ultimately increase yield in a sustainable manner. In addition, we discuss some potential interactions of alternative crop management strategies and some of the requirements for farmers to adopt new management strategies.

Yield Gap Analysis

Wheat yields can be described in various ways:

1. The highest physiological yield where there are no biotic or abiotic constraints (i.e., the highest yield that could theoretically be obtained). This yield is determined by solar radiation and temperature and the genetic ability of the plant to convert light energy into dry matter and subsequently partition this dry matter into harvested yield. Potential yield can be calculated from radiation and temperature data by models for different locations. In northwestern Mexico, potential yield could surpass 10,500 kg/ha, which has been reported in some CIMMYT trials at the CIANO experiment station.
2. The highest achievable yield obtained from maximum yield experiments under field conditions where all inputs are provided without constraint and plants are protected from lodging and biotic stresses (i.e., the highest yield that has actually been obtained). This figure may approach that in

definition 1 but is usually less because some biotic and/or abiotic constraint is present during crop development. The improved wheat variety Super Kauz yielded 8,845 kg/ha (averaged over six years, 1990-95) in CIMMYT maximum yield trials at the CIANO station.

3. The average performance of "normally managed" on-station trials. These trials receive the recommended station fertilizer, irrigation, weed control, and control of other biotic stresses. The plants are not protected from lodging. This yield is sensitive to the level of management set by experiment station managers. As a consequence, yield gaps calculated on the basis of this yield are a bit artificial. The yield from CIMMYT trials at the CIANO station for 1990-95 was 7,219 kg/ha.
4. The average yields obtained by farmers over a certain period. Over 1990-95 in the Yaqui Valley of northwestern Mexico, farmers' yields averaged 4,843 kg/ha.

These four yields are shown in Figure 1, in which gap I, gap II, and gap III represent the differences between the four levels. The objective of any agronomist is to reduce these

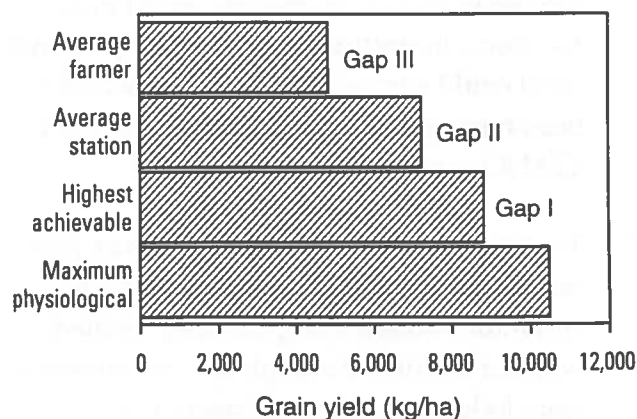


Figure 1. Wheat yield data, Yaqui Valley, northwestern Mexico, 1990-95.

gaps so that farmers can obtain the highest and most profitable yield possible. This can be achieved by analyzing the constraints that prevent higher yields and by developing technical options capable of overcoming these constraints in profitable ways. At the same time, a good agronomist must evaluate the long-term consequences of the different options for natural resource quality and system sustainability.

Sustainable improvement in crop yields requires that all factors affecting yields be set at optimal levels. Von Liebig's "Law of the Minimum" (Paris 1992), a useful way of expressing this relationship, states that yields are constrained by the level of the most limiting factor and that yield improvement depends on the successive removal of binding constraints. In the sections that follow, we will examine the most common factors that constrain wheat yields and suggest ways in which these yields may sustainably be improved through the amelioration of important constraints. Examples are drawn largely from rice-wheat systems in the Indo-Gangetic Plains and from wheat systems in northwestern Mexico.

Nutrients

Von Liebig's "Law of the Minimum," introduced above, is helpful in understanding the role of balanced nutrition in the sustainable improvement of wheat yields. Wheat yields will be constrained by the most limiting macro- or micronutrient. In this section, we examine the nitrogen content and needs of wheat for different yield levels; other nutrients could be examined in the same way. Balancing the uptake of nutrients by the plant with those supplied externally or from the soil is also important for sustaining yield. If soils are mined and more nutrients are removed from

the system than are supplied externally, there will eventually come a time when a nutrient will become limiting and prevent the expression of yield potential. Therefore, it is important to improve nutrient use efficiency and (over the long term) to match nutrient uptake with nutrient supply consistent with a desired level of yield.

The percentage of nitrogen in the wheat straw and grain increases as yield increases, which means that more nitrogen is needed per unit of dry weight as yield increases. The data in Table 1 show the amount of nitrogen in the above-ground biomass at maturity under different harvest index values for various yield levels. Figure 2 shows the percentage of nitrogen in wheat grain and straw at different yield levels.

Some of this nitrogen is obtained from the soil. Each soil has a specific nitrogen supplying capacity (SNSC), depending on soil organic matter content, the mineralization rate of this organic matter, and the availability of the already mineralized nitrogen (nitrate and ammonium) stored in the soil. Perhaps the best

Table 1. Kilograms of nitrogen in the above-ground wheat biomass at maturity for different harvest index values and different yield levels

Yield (kg/ha)	Harvest index			Grain-N (%)	Straw-N (%)
	0.3	0.4	0.5		
1,000	19	17	16	1.45	0.18
2,000	41	37	35	1.53	0.22
3,000	69	62	58	1.68	0.26
4,000	95	86	81	1.75	0.27
5,000	147	132	123	2.10	0.36
6,000	197	174	160	2.19	0.47
7,000	235	207	190	2.22	0.49
8,000	283	246	224	2.25	0.55

Note: Data for grain-N and straw-N are taken from CIMMYT trials in Obregon, Mexico, except for data for the 1,000 and 8,000 kg/ha yield levels, which are estimated based on the data trends.

indicator of SNSC is an estimate of the amount of nitrogen that a wheat crop will take up by maturity, when no nitrogen fertilizer is applied. This quantity can be estimated, without having actually to measure the amount of nitrogen in the above-ground biomass, by knowing the yield when no nitrogen fertilizer is applied (Tables 1 and 2). Table 2 shows the most common wheat yield levels when no fertilizer is applied, 1.5-3.0 t/ha. For example, if the zero-N plot yields 2 t/ha, the soil provides 42 kg/ha of nitrogen. For yields above 3 t/ha, the amount of nitrogen that a soil needs to supply when no nitrogen fertilizer is applied can also be calculated, but at these higher yield levels, an external application of nitrogen is usually needed.

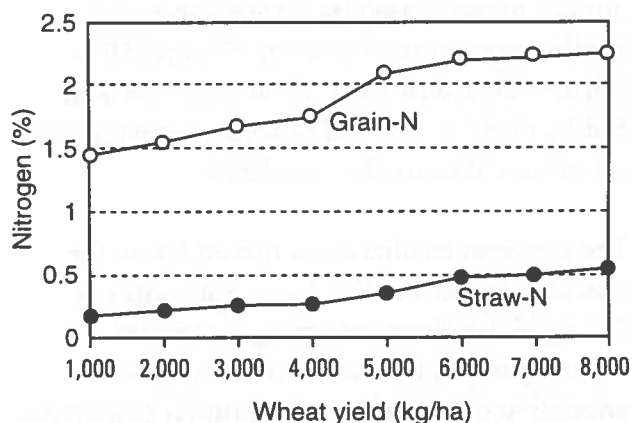


Figure 2. Percentage of nitrogen in wheat grain and straw at different yield levels.

Table 2. Amount of nitrogen that must be supplied by the soil to the above-ground biomass (grain and straw) at a harvest index of 0.41

Yield (kg/ha)	N in grain (kg/ha)	N in straw (kg/ha)	N in above-ground biomass (kg/ha)
1,500	22	7	29
2,000	31	11	42
2,500	40	15	55
3,000	50	19	69

Note: Calculations based on data presented in Table 1.

Table 3 shows how much nitrogen has to be supplied externally to obtain various wheat yields. The data are presented using different nitrogen recovery percentages (the percentage of nitrogen that is recovered by the above-ground plant parts from the external nitrogen applied) and assuming that the SNSC was equivalent to 2,000 kg/ha (42 kg N/ha). Yamaguchi (1991) reviewed the literature of ¹⁵N experiments in wheat and maize (largely from agricultural systems in developed countries) and found a range of 24-85% recovery by the crop; the average value was 57%. On the other hand, estimates of recovery in wheat systems in developing countries have been lower. In the Yaqui Valley of Mexico, estimates from farmers' fields and experiment station trials in which nitrogen rates were similar to those used by farmers showed fertilizer recoveries between 35% and 50% (Ortiz-Monasterio et al. 1994b). Byerlee and Siddiq (1994) estimated nitrogen recoveries in wheat in Pakistan at around 30%.

The nitrogen fertilizer recommendation for wheat over most of the Asian Subcontinent is 120 kg N/ha. Even assuming a nitrogen recovery of 0.8, this rate is obviously not enough to get a grain yield of much more than 5 t/ha (see Table 3). This may explain why

Table 3. External nitrogen that needs to be applied to wheat to obtain various grain yields, calculated at different nitrogen recovery rates

Yield (kg/ha)	Nitrogen recovery percentage			
	30	50	65	80
5,000	300	180	138	112
6,000	447	264	203	165
7,000	550	330	254	206
8,000	680	408	314	255

Note: Calculations assume a harvest index of 0.4 and soil nitrogen supplying capacity equivalent to a yield of 2,000 kg/ha (42 kg N/ha).

scientists have trouble getting higher maximum yields in this region: they do not apply enough nitrogen. Although it is often said that wheat does not respond to nitrogen levels greater than 120 kg/ha, recent experiments show that wheat does respond economically to nitrogen above this level. If no yield response is seen at higher levels of nitrogen application, the lack of response may be related to constraints such as water stress, lodging, and biotic factors (discussed later in this paper).

Ortiz-Monasterio et al. (1994a) compared solar radiation and temperature in India (Ludhiana) and northwestern Mexico (the Yaqui Valley) using the photothermal quotient (PTQ), the mean solar irradiance divided by mean temperature minus the base temperature, for both locations. At similar levels of solar radiation and temperature, the number of grains per square meter, which is highly correlated with yield in both locations, was much lower in Ludhiana than the Yaqui Valley. Ortiz-Monasterio et al. (1994a) have suggested that nitrogen might have been the factor limiting yields in Ludhiana. The implication is that higher yields will require higher levels of nitrogen than are currently applied (or even recommended), combined with practices that remove other constraints, such as lodging, that tend to appear when nitrogen levels are high. Another consideration is that continuous selection for large-grained (high thousand-grain weight) varieties in India may itself limit yield potential, given the strong relationship between yield and grain number per square meter.

Increasing the SNSC is important for improving yields, in part because it helps improve the efficiency of applied nitrogen. However, raising the SNSC is not easy. One way to achieve it is by applying organic

fertilizers, such as manures or crop residues, or by rotating wheat with leguminous plants. The release pattern of these nitrogen sources tends to match the timing of nitrogen uptake by crops, resulting in higher efficiencies. In many developing countries, manure is an important source of pollution, but the costs of hauling manure away and applying it to a field often exceed the value of the manure as a fertilizer – unless manure improves soil quality as well as supplying nutrients. This often is the case. Organic matter lowers soil bulk density and increases water holding capacity, infiltration rate, and aggregate stability. Manures are essentially slow release fertilizers, providing a stable supply of the ammonium ions needed for high yield. Organic phosphates and chelated micronutrients found in manures are slowly released to the plant. They can also provide biotic factors that antagonize root diseases. Thus manures essentially improve the properties of soil as a growing medium. Data presented in Table 4 present the effect of using poultry manure and subsoiling on wheat in northwestern Mexico compared to the control,

Table 4. Effect on wheat yield (kg/ha) of applying poultry manure to wheat, with and without subsoiling, CIANO Station, Sonora, northwestern Mexico

Factor	With subsoiling	Without subsoiling	Mean, poultry manure
With poultry manure	8,005	7,575	7,790 a
Without poultry manure	7,075	6,915	6,995 b
Mean, subsoiling	7,540 a	7,245 b	

Note: Results are from an 11-year trial (1987-97). Subsoiling was to a depth of 60 cm with 75 cm between subsoil shanks. Poultry manure was applied at a rate to supply 150 kg N/ha. Crop rotation was Sesbania (green manure) - wheat. Means in rows or columns followed by the same letter do not differ significantly at LSD (0.05). The subsoil * poultry manure interaction was significant at 0.001 level and the interaction LSD (0.05) = 636 kg/ha.

on which these two management practices were not used. These practices can raise yields by nearly 800 and 300 kg/ha, respectively.

Unfortunately, supplies of organic fertilizers are declining in many parts of the world, even in China, where organic fertilizers have always been a major component of fertilizer strategies. In South Asia, some reasons for this decline are:

- Animal numbers and therefore manure supplies are declining as tractors are increasingly used for farm operations. The cost of maintaining a pair of bullocks for a year is becoming prohibitive.
- Animal manure is used increasingly as cooking fuel (Fujisaka, Harrington, and Hobbs 1994; Harrington et al. 1993).
- Higher labor costs make moving the heavy manure to fields, especially those far from the homestead, uneconomic.

In the rice-rice and rice-wheat systems of South Asia, long-term fertilizer experiments on research stations have indicated that yields and total factor productivity have declined over time for both crops when grown at constant recommended fertilizer levels (Cassman and Pingali 1995; Cassman et al. 1996; Pagiola 1995; Nambiar 1995; Regmi 1994). Farmers also report the need to increase the amount of fertilizer in order to maintain yields at previous levels. Agronomists need to understand the reasons for these productivity declines, including the biophysical processes that underpin them, if they are to succeed in reversing them.

A decline in soil organic matter (SOM) or changes in SOM quality have been hypothesized to cause this sustainability problem (Cassman et al. 1995). Soil organic matter is declining throughout the rice-wheat belt of the Indo-Gangetic Plains of South Asia (Nambiar 1994). Applications of farm yard manure reduce the

rate at which SOM declines. Experiments at the International Rice Research Institute (IRRI), though, indicate that maintaining or building up SOM does not necessarily result in a higher or sustained nitrogen supply. The total size of the SOM in soils may be less important than the size and activity levels of the active fraction that is involved in nutrient cycling. Cassman et al. (1995 and 1996) and Olk et al. (1996) have hypothesized that changes in the quality of SOM as a result of continuous flooding in rice-rice systems lead to decreased SNSC. Is the same problem occurring in rice-wheat systems, in which the soil is not continuously in a reduced state because of flooding? The roles of SOM and SNSC in sustaining high wheat yields require much more research.

Another way to improve nitrogen availability is to increase the use efficiency of externally applied nitrogen. Developing countries cannot achieve food security without some external application of nutrients, including nitrogen. At the same time, the public health and environmental costs of nitrate pollution of groundwater and of nitrous oxide emissions into the atmosphere are important and cannot be ignored. The goal of an agronomist must be to enhance the use efficiency of applied nutrients, while minimizing undesirable environmental impacts.

Improvements in matching the nitrogen demand from the crop with the nitrogen supply can increase nitrogen recovery efficiency. This can be accomplished in different ways. One way is to use split fertilizer applications. Another method relies on chemicals, such as nitrapyrin, which inhibit the conversion of ammonium to nitrate in the soil; this method has shown some promise, but the results are inconsistent, varying largely from soil to soil. Two other options are the use of urease inhibitors (to slow the hydrolysis of urea, which is particularly

effective in surface applications) or slow-release fertilizers (generally covered with sulfur or polyurethane, which take several weeks to break down).

Still another possibility is to apply nitrogen in a band below the ground rather than broadcasting it on the soil surface. In many wheat-growing areas of the world, most nitrogen applied after planting is applied as a top-dress on the soil surface. It would be difficult to change this practice in fields commonly planted in dense stands. However, the use of bed-planting systems, which are described later in this paper, would enable farmers to improve fertilizer efficiency by placing top-dress fertilizer applications and incorporating fertilizer.

In evaluating several nitrogen application strategies in northwestern Mexico, Ortiz-Monasterio et al. (1994b) found that delaying the application of different rates of nitrogen until first node formation resulted in increased yield or the same yield as when all the nitrogen was applied at planting (Figure 3). In addition, delaying all nitrogen application until first node resulted in a dramatic increase in the flour protein concentration (Figure 4). It was also found that at 225 kg N/ha there was further improvement in nitrogen use efficiency if one-

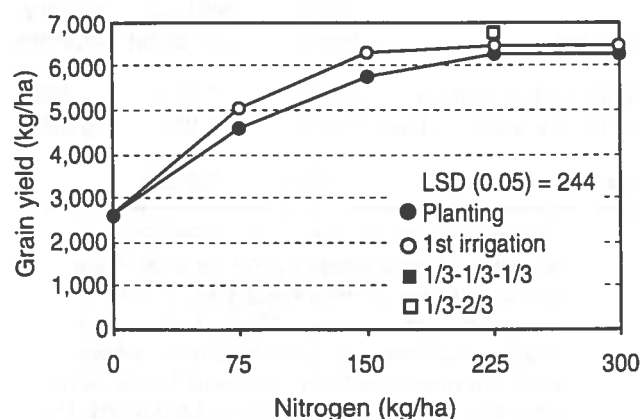


Figure 3. Response of grain yield to different rates and timing of nitrogen application.

third of the nitrogen was applied at planting and two-thirds was applied before first node. This improvement was reflected in a higher yield (Figure 3) and a higher nitrogen recovery by the crop (Figure 5). Table 5 shows that these relationships hold for a number of genotypes of bread and durum wheat at a level of 150 kg N/ha. Although these results were obtained on soils with high initial soil nitrogen, they do show that in some situations nitrogen use efficiency can be increased by delaying the application of some nitrogen to just before first node formation.

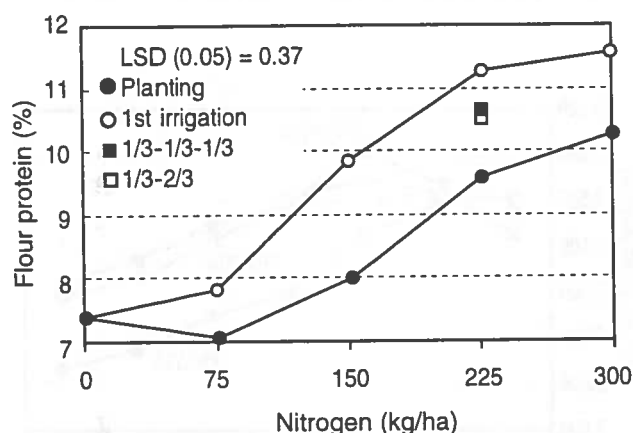


Figure 4. Response of flour protein to different rates and timing of nitrogen application.

Fischer, Howe, and Ibrahim (1993) conducted experiments in Australia to determine how long a single supplemental application of nitrogen to the wheat crop could be delayed and still elicit a full grain yield response. A significant yield loss did not occur until nitrogen was applied just after first node initiation (just after the onset of stem elongation). Nitrogen recovery ranged from 44% to 77% and did not decline until nitrogen was applied after stem elongation. In fact,

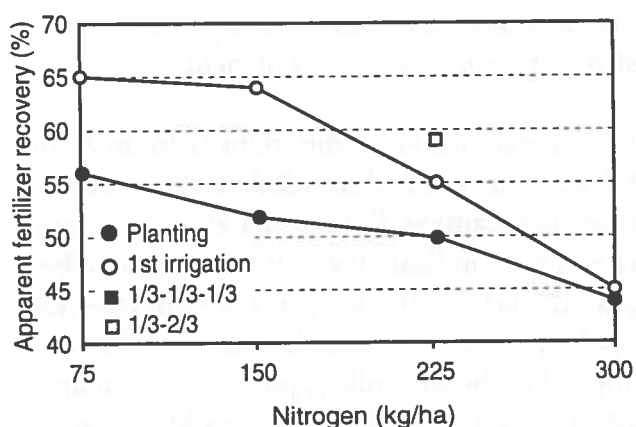


Figure 5. Response of percent apparent fertilizer recovery to different rates and timing of nitrogen application.

Table 5. Comparison of the application of 150 kg N/ha at planting and first node on grain yield and grain protein percentage for various wheat genotypes

Genotype	Grain yield (kg/ha)		Grain protein (%)	
	Basal	First node	Basal	First node
Rayon 89 (BW)	6,722	6,712	12.36	12.27
Oasis 86 (BW)	6,011	6,634	10.73	11.86
Weaver (BW)	5,830	6,413	11.49	12.26
Opata 85 (BW)	6,089	6,661	11.50	12.21
Bacanora 88 (BW)	6,577	6,504	10.74	12.04
Baviacora 92 (BW)	6,322	6,594	10.39	11.21
Aconchi 89 (DW)	5,447	6,719	11.73	12.68
Altar 84 (DW)	6,215	6,841	11.49	11.97
Mean	6,152a	6,635b	11.30a	12.06b

Note: Means followed by different letters are significantly different using the LSD test at 0.05 probability. LSD values are 379 kg and 0.72% for the grain yield and protein percent, respectively. Based on data from CIMMYT, Mexico.

nitrogen recovery increased slightly when nitrogen was applied later (up to stem elongation) compared to when it was applied earlier.

Chinese scientists in the Yangtse River Valley also recommend delaying nitrogen applications for higher yields. They have developed a system called "green-yellow-green," in which some nitrogen is applied early, but the crop is then given a nitrogen stress during the main vegetative phase. At the first node, the rest of the nitrogen is applied. This results in less luxury biomass and stronger stems, but no loss of yield.

Fertilizer timing is an important factor in zero-tillage systems, in which fertilizer cannot be placed at planting. Data from Pakistan (Aslam et al. 1993a) indicate that if nitrogen cannot be placed it is better to delay its use until later and apply it as a top-dressing (Figure 6). Nitrogen applied in the zero-tillage plots was taken up 20% less efficiently than in the traditionally planted plots, where the basal nitrogen was incorporated.

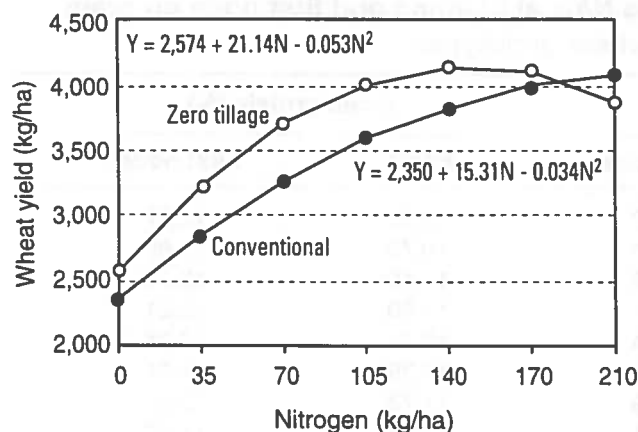


Figure 6. Nitrogen response for wheat under conventional and zero tillage from seven experiments in farmers' fields, Punjab, Pakistan.

Planting Date and Crop Establishment

It is well known that substantial increases can be realized in wheat yields in the Indo-Gangetic Plains if wheat is planted on time and plant stands are good. Figures 7 and 8, which are based on data from the Indian Punjab, show responses of wheat to different dates of planting which are typical for many other areas of the world. Each figure shows that there is an optimum date for planting, which is followed by an almost linear decline in yield after that date. There are differences between varieties:

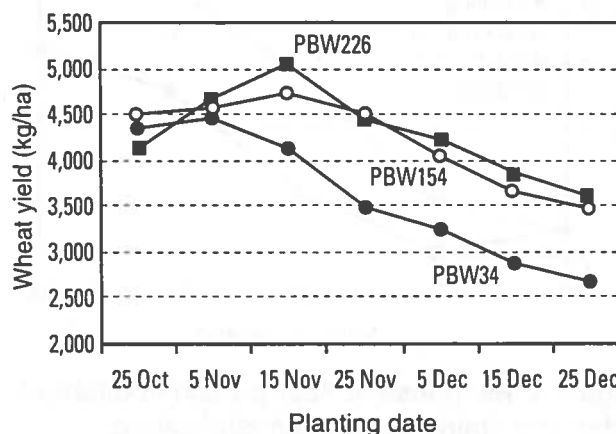


Figure 7. Effect of planting date on wheat yield, by variety, Punjab, India.

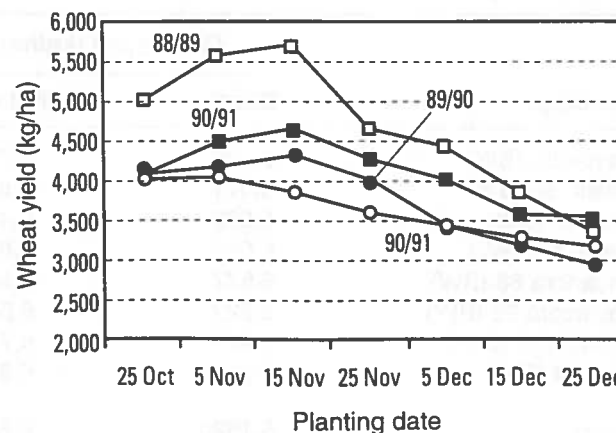


Figure 8. Effect of planting date on wheat yield, 1987/88 to 1990/91.

some genotypes are more stable over a range of planting dates than others (Figure 7), and the shape of the curve also varies over years (Figure 8). Declines of 0.7-1.5% per day of delay in planting after the optimal date of planting are common (Saunders 1990; Hobbs 1985; Randhawa, Dhillon, and Singh 1981; Ortiz-Monasterio et al. 1994a).

The theory behind the loss in yield at later dates of planting can be related to the effect of the PTQ. Fischer (1985) and Midmore, Cartwright, and Fischer (1984) showed that kernel number is associated with the PTQ over the 30 days before anthesis. In Figure 7, the optimum date of planting for the longer maturing variety (PBW34) was 5 November; the optimum date for the two shorter duration varieties was 15 November. When these three varieties were planted at these optimum dates, they all reached anthesis at the same date (Ortiz-Monasterio et al. 1994a), which coincided with the time of year when the PTQ for that location was highest. The highest yield in this location was obtained when the PTQ value at 20 days before heading and 10 days after heading was maximized. Additionally, higher temperatures close to the flowering and grain filling periods of late-planted wheat

Many factors can cause wheat to be planted late. In the intensive, irrigated cropping systems of the Asian Subcontinent, late harvest of the previous crop and the long turnaround between rice harvest and wheat planting are two of the major causes of late wheat planting (Hobbs, Giri, and Grace 1998). Excessive tillage, unfavorable soil conditions, and poor power sources are common reasons for long turnaround in South Asia (Hobbs, Bronson, and Meisner 1996). Late harvest of cotton and basmati rice commonly delays wheat planting.

One solution to this problem is to introduce reduced and zero-tillage options to farmers, with the objectives of reducing turnaround time and planting wheat closer to the optimum date. Research over the past decade in the rice-wheat areas of South Asia, on farmers' fields as well as experiment stations, has identified several tillage options to cope with this problem (Hobbs, Bronson, and Meisner 1996; Hobbs, Giri, and Grace 1998).¹

1. Wheat is surfaced seeded onto unplowed soil either before or just after the rice harvest. The key to this system is maintaining proper soil moisture at seeding and during initial root extension. This system is particularly relevant on finely textured, poorly drained

Errata:

Figure 6, p. 8: Zero tillage and conventional tillage are switched.

Figure 8, p. 8: Top line should be 89/90, followed by 91/92, 89/90, and 87/88.

wheel tractors are available. Local artisans are producing the equipment and selling it at prices within farmers' budgets, and the practice is gaining popularity in India and Pakistan in fields where rice stubble is not too much of a problem.

3. Another option is to prepare the soil and plant in one operation. This reduced-tillage option utilizes a shallow rotovator ahead of a seed drill, followed by a roller. A two- or four-wheel tractor can power this machinery. The introduction of two-wheel Chinese tractors in Bangladesh, Nepal, and eastern India will be particularly relevant for small-scale farmers who are finding it excessively expensive to continue keeping bullocks for plowing. These two-wheel tractors can also be hooked up to other implements for threshing, pumping, reaping, deep plowing, and transport.

Data are being compiled in the Asian Subcontinent on the establishment of wheat after rice, under zero and reduced tillage. Table 6 shows some of the data from Nepal, in which wheat grown under surface seeding and reduced tillage with the Chinese drill is compared with wheat grown under the traditional system. With surface seeding and reduced tillage, wheat yields and thousand-grain weights are higher, and production costs are lower. Data from Pakistan (Table 7) show

that zero tillage with an inverted-T coulter drill will give better yields than traditional planting, with greater benefits where planting is closer to the optimum date. On average, more than one ton of extra yield was obtained with zero tillage compared to the farmers' practice, and planting was 24 days earlier. Data are also being compiled in India and Bangladesh on this innovative, cost-reducing technology. What is needed is more support from research and extension directors to help farmers become better acquainted with these options (and how they perform in different wheat systems), as well as better links with private sector

Table 7. Comparison of zero-tillage and farmers' practice for establishing wheat after rice in locations in the Pakistan Punjab where the planting dates for the two methods differed

Location	Wheat yield (kg/ha)		
	Zero-tillage	Farmers' practice	Days difference
Daska, site 2	3,143	3,209	10
Daska, site 1	3,842	2,735	13
Ahmed Nagar	4,308	3,526	20
Maujjanwala	2,689	2,198	22
Mundir Sharif	4,245	2,660	33
Daska, site 3	3,838	3,420	44
Average	3,677 a	2,598 b	24

Source: (Aslam et al.1993).

Note: Means followed by the same letter do not differ significantly at the 5% level using DMRT.

Table 6. Data from a wheat establishment trial following rice, Bhairahawa Agricultural Farm, Nepal, 1993/94

Method	Yield (kg/ha)	1,000-grain weight	Cost to plow (Rs/ha)	Net benefit (Rs/ha)	Extra days needed to plant ^a
Surface seeding	2,775 a	46.11a	0	11,485 a	0
Chinese seed drill	2,831 a	45.43b	600	12,090 a	8
Farmers' practice	2,314 b	40.87c	2,300	8,065 b	15

Source: (Hobbs and Giri 1998).

Note: Figures followed by the same letter are not significantly different at 5% probability using DMRT.

^a Number of extra days needed for land preparation before seeding compared to the surface seeding.

equipment manufacturers. Ultimately, only the private sector is in a position to meet any unfolding demand for new tillage and establishment machinery for wheat systems.

Tillage and establishment practices are important factors in the sustainability equation for wheat systems in the Indo-Gangetic Plains. Farmers use tillage to help control weeds, develop a good seedbed, and control crop residues. However, excessive tillage unnecessarily consumes vast amounts of energy. It also results in soil compaction, increases the likelihood of erosion, fosters more rapid decomposition of organic matter, and enhances the germination of weed seeds.

Much information is being released on the long-term benefits of reduced- and zero-tillage systems. Although much of this research is focused on developed countries, some of the results may nevertheless contribute to the design of research in developing countries. A six-year trial in New Zealand resulted in improved soil physical properties with direct drilling compared to conventional cultivation (Francis, Cameron, and Swift 1987). Zero tillage resulted in better aggregate stability, more earthworms, a more open and continuous network of soil pores, more roots in the top 100 mm of soil, and the same yield at lower cost. Guo Shaozheng et al. (1995), who studied zero and minimum tillage in wheat for 25 years in an area where soils are heavy and plant stands are poor, report that conservation tillage helps to preserve surface soil moisture, improve plant stands, and improve soil structure. Conservation tillage has reportedly been adopted over one million hectares in Jiangsu Province, or 80% of the total area where wheat is grown after rice. However, Guo Shaozheng et al. (1995) note that after three to four years, the soil must be deeply plowed to improve soil physical and chemical properties and weed control.

Many researchers report no yield sacrifice by reducing tillage. Different results are reported in regard to disease incidence. Herman (1990) reported that zero-tillage plots had higher antagonistic activity by rhizosphere flora (measured by better observed growth), and less incidence of *Gaeumannomyces graminis*, than in conventionally tilled plots. Work in Australia has shown higher levels of crown rot in zero-tillage treatments of wheat. Crown rot was associated with retention of the stubble (Dodman and Wildermuth 1989). In the rice-wheat systems of South Asia, opponents of zero tillage cite problems of insects and weeds to discourage the introduction of this technology. However, Inayatullah et al. (1989) found that rice stem borers were not a problem as first hypothesized. When a crop of wheat is grown with irrigation and fertilizer, stemborer populations fall as the rice stubble decays. Weeds such as *Phalaris minor*, a major problem in rice-wheat systems, are also found to be lower in zero-tillage plots than in conventionally tilled plots because the soil is disturbed less.

Agronomists and farmers need to collaborate in the development of complementary practices – soil fertility, water, and nutrient management practices – to facilitate widespread adoption of reduced and zero tillage options across a range of wheat systems. By reducing tillage, the sustainability of food production can be increased through less fuel consumption and wear and tear on tractors and implements, better input efficiency, and, in some cases, higher yields because of more timely planting.

Water Management

Sustainable increases in wheat system productivity depend on adequate levels of water as well as adequate levels of nutrients.

development of appropriate machinery for making and planting beds, this bed-planting system would appear to have several main advantages:

- It improves water distribution and efficiency.
- It improves fertilizer efficiency by enabling farmers to place the pre-plant fertilizer applications below the bed. Top-dress nitrogen can also be placed in the furrows or on the bed and incorporated before irrigation.
- It provides an alternative for weed control, because the furrows can be cultivated. This will be discussed in more detail later.
- It helps reduce lodging because the wheat plants are not exposed to soft soil conditions after irrigation, and more light can penetrate the canopy, resulting in stronger plants.
- It can potentially allow dramatic reductions in seed rates (Table 9).

With regard to sustainability, the FIRBS system combines the benefits of reduced tillage with the benefits of water efficiency. By reducing the tillage, farmers save on production costs, which leads to higher profits or cheaper food production. Savings in fuel and equipment would be substantial. Better irrigation systems would reduce groundwater pollution and the problems of salinity and waterlogging, which are often associated with poor water management. In parts of northwestern India, where water tables are falling at significant rates, substitution of upland crops such as soybeans or maize, grown on permanent bed systems with wheat in place of rice, may help slow this natural resource problem.

Lodging

Cereal genotypes grown by farmers before the identification of the Norin 10 dwarfing genes (*Rht1*, *Rht2*) were prone to lodging at low yield

Table 10. Wheat yield (kg/ha) averaged over four years for tillage/straw management and nitrogen management treatments for a bed-planted wheat (W) and maize (M) rotation

Nitrogen (kg/ha)	Tillage/straw management					Nitrogen mean
	Conventional (W-incorporate, M-incorporate)	Reduced (W-burn, M-burn)	Reduced (W-partial, M-remove)	Reduced (W-retain, M-remove)	Reduced (W-retain, M-retain)	
0 N	3,105	3,188	3,147	3,834	3,332	3,321 a
75 N basal	4,024	4,650	4,572	4,455	4,914	4,523 b
150 N basal	5,435	5,809	5,475	5,626	5,742	5,615 c
225 N basal	5,910	6,393	6,007	6,063	6,480	6,171 d
300 N basal	6,212	6,700	6,520	5,949	6,660	6,408 e
150 N 1 st node	5,876	5,988	5,687	5,917	6,023	5,898 d
300 N 1 st node	6,356	6,342	6,453	6,167	6,731	6,410 e
Tillage/straw management mean	5,274a	5,581c	5,409ab	5,430b	5,697c	..

Note: Means in rows or columns followed by the same letter are not significant by LSD (0.05) for interaction = 408 kg/ha. Reduced tillage consists simply of forming the bed again after each crop in the rotation. No soil inversion is practiced. For straw management, "incorporate" = burying all the straw; "partial" = removing the straw cut by the combine but leaving the standing wheat stubble; "remove" = complete straw removal; and "retain" = chopping and leaving all straw in place on the surface. "1st node" = first node stage of development.

levels. With the incorporation of these dwarfing genes into wheat and rice in the 1960s, the resulting modern varieties possessed not only higher yield potential but also good lodging resistance (the latter resulted from shorter and stiffer straw) (Fischer and Wall 1976; Pinthus 1973; Vogel, Allan, and Peterson 1963; De Datta, Tauro, and Balaoing 1968). The effect of lodging in older, traditional varieties was studied using artificial means, and a yield loss in the range of 30-40% was reported when lodging occurred close to heading and somewhat less when it occurred later (Pinthus 1973).

Similar artificial lodging studies were conducted on modern, shorter varieties in the early 1970s in Mexico (Fischer and Stapper 1987). Culm lodging to an almost horizontal position caused grain yield to be reduced by 7-35%. Lodging losses were greater when they occurred in the first 20 days after anthesis and were significantly less when lodging occurred before anthesis or more than 20 days after anthesis. The greater the angle of bending of the culm, the greater the yield loss. Fischer and Stapper (1987) suggested that plants were able to right themselves by node bending when lodging occurred before anthesis. They also showed that kernel number per unit area was reduced by early lodging and kernel weight by later lodging together with a small increase in grain nitrogen percentage. Fischer and Stapper also pointed out that the percentage of sprouted grain could increase with lodging and suggested that even more yield loss would occur where combine harvesting was done. These researchers also reported results of trials with natural lodging in which grain yield was reduced up to 37%. However, their results were difficult to interpret because lodging in any one plot could occur at different growth stages.

In Australia, lodging experiments produced similar results (Stapper and Fischer 1990c); yield reductions from lodging were as high as 45%. Stapper and Fischer concluded that high yields under irrigation could be achieved consistently and efficiently only with genotypes that resist lodging (because of their short, stiff stems) or avoid it (by maturing early). Interestingly, even double dwarf genotypes lodged at high yield levels. This suggests that lodging is a major problem for wheat produced under irrigation, especially at yield levels higher than 5.5 t/ha. Researchers in the Indian Punjab have trouble breaking the 5.5-6.0 t/ha yield barrier in their trials, even though the yield potential of the varieties in those trials should be at least 8 t/ha. Two constraints related to lodging may be limiting yields in India.

First, researchers use no more than 150-180 kg of nitrogen in their maximum yield trials. Past experiments have shown no response above this nitrogen level, but as explained earlier, this nitrogen level is insufficient to produce yields above 5.5 t/ha under average conditions. However, at higher nitrogen levels wheat plants probably lodge when the recommended irrigation is given. Second, researchers tend to avoid the last irrigation (at grain filling) because it results in lodging. This practice may have resulted in water stress at this critical stage and thus in reduced yield. Thus the combination of limiting nitrogen and water could explain the inability to break the 5.5-6.0 t/ha yield barrier encountered in experimental plots.

It would be appropriate to investigate this hypothesis by conducting an experiment in the Punjab with various genotypes with and without physical support (netting) to prevent lodging, making sure that nitrogen and water are not limiting and that there are no compaction layers or biotic stresses. (Similar

experiments have been conducted in northwestern Mexico.) If results show that lodging is a major factor limiting yields, especially at the higher yield levels (greater than 5.5 t/ha), then future research should give greater emphasis to this issue.

Lodging risk increases with increased dry weight at anthesis and for taller crops; both traits are associated with the duration from sowing to anthesis (Stapper and Fischer 1990a, 1990b). Other traits, however, are associated with resistance to lodging, including height, stem stiffness (biochemical composition), angle of roots, and shoot density. Studies are underway in Mexico to identify genotypes with these traits and to incorporate them into new varieties. Note that some taller varieties with a single dwarfing gene, such as Baviacora 92, are much taller than varieties with double dwarfing genes yet lodge less. It is thought that their root systems, which spread out more, are responsible for this difference.

Several management strategies can also be used to decrease the effect of lodging and raise yields. First, as mentioned earlier, the timing of irrigation is crucial. This poses a dilemma, as water must be supplied at the critical stages of flowering and grain filling to obtain a good yield, but lodging often accompanies irrigation at these growth stages. When wheat is grown on the flat, irrigation will create a wet condition around the roots, where soil strength is not sufficient to support the plant. Growing wheat on beds (discussed earlier) instead of on the flat is one way to adjust irrigation and to prevent the wet soil surface that will lead to lodging, especially under windy conditions. Another advantage of the beds is that they drain faster, therefore leaving the crop vulnerable to lodging for a shorter period of time.

Second, nitrogen timing can be adjusted to reduce lodging. By delaying the nitrogen application until just before first node, excessive foliage is reduced, stems are less etiolated and stronger, and lodging should be less (Table 11).

A third management strategy, developed by Chinese researchers, is to plant wheat in a skipped row configuration for yields above 5.5 t/ha (Guo Shaozheng, pers. comm.). In this system, two paired rows are planted and the third row is skipped, resulting in a configuration similar to ridge-and-furrow planting. Of course, farmers must then ensure that nitrogen and water are not limiting. The theory is that more light enters the canopy, resulting in stronger plants.

Fourth, various growth hormones that reduce plant height can be used to diminish lodging. These are commonly used in Europe, where some of the highest yielding commercial wheat crops are produced. However, some studies have shown that growth regulators do not always work. Fischer and Stapper (1987) reported that growth regulator was applied at

Table 11. Strategies for applying 225 units of nitrogen fertilizer and resulting effect on lodging

Nitrogen treatment ^a	Initial soil nitrogen level				
	Low	Low-medium	Medium	High	Mean
225/0/0	5.0 ^b	5.0	5.0	5.0	5.0
0/225/0	1.6	4.0	2.3	3.6	2.9
0/0/225	1.0	1.3	1.0	1.3	1.1
75/150/0	5.0	4.6	5.0	5.0	5.0
75/75/75	4.3	5.0	5.0	5.0	5.0

^a The three numbers refer to the rate of N applied at three different times: planting, first irrigation (close to first node), and second irrigation (early booting).

^b Lodging values are on a scale of 1 to 5, in which 1 = 0% lodging and 5 = 100% lodging.

the correct stage and that it reduced plant height but did not sufficiently reduce lodging to give a yield advantage. However, in this experiment, lodging commenced before the first application of the regulator. Figure 9 shows data from a trial in Mexico in which two varieties were sprayed with Ethephon, a plant growth regulator. Lodging was significantly reduced by this treatment. More work is needed on this subject.

Finally, vigorous rooting should also help reduce lodging. Use of organic manures and removal of any physical root barriers should promote good rooting.

Weed Control

Any organism that competes with wheat for light, water, or nutrients will reduce wheat yields. Weeds are a good example of this relationship: without proper control, broadleaf and grassy weeds can significantly limit wheat yields. In the irrigated, high-yielding wheat areas of northwestern Mexico and the Asian Subcontinent, it is the two grassy weeds *P. minor* and *Avena fatua* that cause major yield losses.

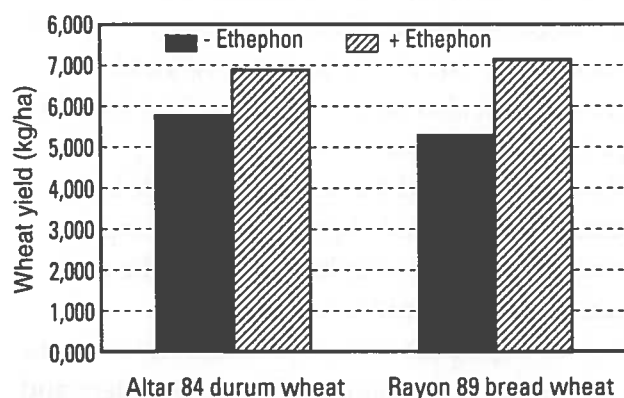


Figure 9. Effect of Ethephon on yield of two wheat varieties.

As observed earlier, several crop management options, including rotations, alternative tillage strategies, and bed-planting systems, offer potential for controlling weeds and improving wheat yields sustainably. Herbicides are another weed control option, but greater attention must be given to alternative control methods and to ensuring that chemicals are used properly to reduce health risks and environmental damage. Herbicides are less effective if improperly applied — for instance, at the incorrect time and dose, or without appropriate adjuvants. This is a common problem in the Asian Subcontinent, where many farmers lack the correct spraying equipment to apply chemicals uniformly and also lack knowledge of proper doses and application methods. In fact, many farmers in India and Pakistan apply Isoproturon, a good grassy weed herbicide, by broadcasting it with sand or urea.

Improper herbicide use has probably contributed to the herbicide resistance that is appearing in *P. minor* and *A. fatua* in Mexico and India (Malik 1996; Malik and Singh 1995). The use of new herbicides or a mixture of herbicides is one alternative and will remain a part of the weed control strategy, but other control methods are needed because weeds are likely to develop resistance to these new herbicides over time.

In integrated weed management, the use of chemicals, rotations, cultivation, and other management practices such as bed planting are all part of the weed control package. A few examples follow.

- As discussed previously, one advantage of growing wheat on beds in a ridge-and-furrow system is that farmers can cultivate between the furrows. When combined with nitrogen top-dressing, this system is even

more efficient. Data also suggest that growing wheat this way creates a drier soil surface next to the stems and reduces *P. minor* growth, since *P. minor* prefers a moister soil. This system is being examined in Mexico and India as an important alternative for control of herbicide-resistant *P. minor*.

- Data from South Asia suggest that the populations of *P. minor* in zero-tilled plots are smaller than in traditionally established wheat (Majid et al. 1988; Aslam et al. 1993b). It is hypothesized that zero tillage reduces disturbance of the soil and that fewer weed seeds are exposed for germination, and studies have been initiated to exploit this possibility for controlling grassy weeds. It is proposed to irrigate fields after the rice harvest and allow the first flush of resistant *P. minor* to germinate. This flush is controlled with a nonselective herbicide, glyphosate (Roundup). The fields are then planted by zero tillage to reduce weed germination. If required, selective chemicals can be used to control later flushes.
- Rotations form a major part of farmers' weed control strategies. In northwestern India, farmers commonly grow sugarcane and its ratoons for two to three years before returning to wheat (Hobbs et al. 1991, 1992; Fujisaka, Harrington, and Hobbs 1994). Break crops such as sunflower and *Brassica* spp. are used more and more by farmers in India and Pakistan during the wheat season. If the sunflower is grown on beds or in rows, intercultivation can be done, with even better weed elimination.

All of these weed control practices have implications for the sustainability of wheat production. The example of herbicide resistant weeds in rice-wheat systems of South Asia highlights the risks of depending on chemical

control strategies. A sustainable system would be based on an integrated approach to controlling weeds or other biotic problems. When a bed-planting system is used for planting wheat, weeds can be removed from furrows by intercultivation. The use of stubble as mulch can also suppress weed growth. Where noxious weeds are present, low doses of herbicide, combined with some cultivation, can be effective. Rotations can also help reduce weed populations; the introduction of sugarcane into rice-wheat areas of western Uttar Pradesh is a good example of using rotations to control *P. minor*. Rotations also provide other benefits that contribute to sustainably improving wheat yields, such as improvement of soil physical properties, breaking of disease and insect pest cycles, and improvement in soil fertility. Legumes are often cited as a means of improving soil fertility, especially when they are grown as fodders or green manures. All of these issues must be considered in developing a strategy to increase yields and meet the growing demand for wheat.

Conclusion

As this paper has attempted to demonstrate, the potential for achieving sustainable increases in wheat yields throughout the world is still considerable. Food security will depend not only on our ability to improve yield growth, but also on our ability to improve this yield growth in such a way that food prices remain stable and the natural resource base remains unharmed. Agronomy and crop management research hold some of the most exciting opportunities for sustainably improving wheat system productivity in areas such as the Indo-Gangetic Plains. Breeders and pathologists play an important role by providing genotypes that have high yield

potential and resistance to biotic and abiotic stresses, including lodging, and that use water, nutrients, and other resources more efficiently. Agronomists contribute by developing strategies for farmers to exploit the yield potential in these genotypes in ways that are not detrimental to the natural resource base. This paper has given examples of several promising strategies, especially tillage and nutrient management practices, whose adoption may make the difference between food security and food scarcity in the years to come.

In the next two or three decades, it is imperative that scientists from various disciplines continue working on farmer-identified problems at specific sites to refine technologies that sustainably increase yields. It is essential for these researchers to work closely with farmers and extension personnel, both in the public and private sectors as well as in non-governmental organizations, to ensure that the newly developed technology is relevant, available, and that farmers can quickly accept and use it to increase food production.

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