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Ensuring the Use of Sustainable Crop Management Strategies by Small Wheat Farmers in the 21st Century

K.D. Sayre[1]

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CIMMYT

Sustainable Maize and Wheat Systems for the Poor

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Preface

Among the most exciting options available today to improve the productivity and sustainability of wheat systems are new conservation/zero tillage and residue management practices. However, for the most part, modern, sustainable crop management strategies have by-passed small-scale farmers, especially small wheat farmers, in the developing world. The reasons for this are many and varied, depending on whether the cropping environment is irrigated or rainfed.

Conservation tillage research has focused mainly on rainfed situations, where crop residue retention to enhance both erosion control and moisture retention is of paramount importance. In contrast, the application of conservation tillage to irrigated cropping systems, especially those including wheat, has been very minor throughout the world. For the past seven years, CIMMYT's wheat agronomy group has been working on a bed-planting system that combines reduced or zero tillage with residue retention, providing unique opportunities to reduce tillage and manage crop residues in irrigated cropping systems.

Planting wheat on beds with conventional tillage under irrigation is not new. However, the technology has been dramatically changed by researchers and farmers in northwestern Mexico over the past 20 years. Its success in the region (more than 90% of farmers have adopted it) has prompted CIMMYT researchers to investigate its potential in other parts of the world.

As part of that effort, CIMMYT has recently begun to explore the application of permanent beds to wheat-based rainfed production systems. As documented in this special report, we are finding that permanent beds can provide small-scale wheat farmers in rainfed environments with a valuable technology that allows them to reduce tillage, conserve moisture, and use a major part of the crop residue for fodder. Based on these positive results, we are convinced that bed-planting offers a sustainable method for planting wheat in both rainfed and irrigated conditions that small-scale farmers will adopt and continue to apply well into the 21st century.

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Abstract

Virtually all current strategies to implement modern, sustainable crop management production practices involve conservation/zero tillage prior to seeding, some form of crop residue retention and management, fertilizer application methodologies that minimize nutrient losses, and integrated insect, disease, and weed management practices that rely on minimal or no use of pesticides.

In nearly all instances, the use of these modern, sustainable crop management strategies has by-passed most small farmers (especially small wheat farmers) in developing countries for several reasons, including: 1) the lack of small-scale planters that are compatible with two-wheel or small four-wheel tractors, or with draft animals, and appropriate for sowing into residues in reduced or zero tillage systems; 2) the need of many farmers to remove or pasture crop residues for livestock feed or to remove residues for cooking fuel; 3) the lack of knowledge by small farmers (and most researchers) about how best to apply fertilizers (when and where, with main emphasis on nitrogen fertilizers) to minimize losses while complementing farm level nutrient sources, including farmyard manure/composts and/or green manures, especially when combined with reduced or zero tillage systems; and 4) the largely unknown ramifications of these practices, which may modify insect, disease, and weed incidence.

Research is underway at different institutions in several countries to address these problems and help ensure that sustainable crop management practices relevant to small wheat farmers will become a reality. Some of these efforts will be discussed here, including ongoing work at CIMMYT on the application of bed-planting in wheat production systems.

Ensuring the Use of Sustainable Crop Management Strategies by Small Wheat Farmers in the 21st Century

K.D. Sayre

Introduction

The implementation of conservation tillage practices is widely considered to be essential to the maintenance, restoration, and/or improvement of the sustainable productivity base of most arable crop production systems. This is certainly true for highly erodable hillside areas under annual crop production and for other potentially fragile cropping systems where soil physical, chemical, and biological parameters appear to be deteriorating (Phillips and Phillips 1984).

There are nearly as many definitions of conservation tillage in the literature as there are scientists who are involved in tillage research. For the purpose of this paper, conservation tillage is broadly defined as a tillage system that leaves enough crop residue to adequately protect the soil from erosion throughout the year (Reeder 1992). Zero-tillage is a category of conservation tillage in which the soil is left undisturbed from the harvest of one crop to the seeding of the next crop, with only slight soil disturbance associated with creating a narrow slot in which to place the seed (and in some cases, fertilizer) (Dickey 1992). Obviously this latter definition implies that crop residues are also managed to provide adequate erosion control.

These definitions reflect the fact that most conservation tillage research and implementation have focused mainly on rainfed situations where crop residue retention to enhance both erosion control and moisture retention is of paramount importance. In cool, high rainfall, rainfed conditions, however, the retention of crop residue can aggravate stand establishment and facilitate disease development if the residues are not managed properly and/or if proper rotations are not followed.

In contrast, the application of conservation tillage to irrigated cropping systems, especially those including wheat, has been very minor throughout the world, except for several small areas where sprinkle irrigation is used (Zimbabwe, for example). Where gravity-applied irrigation is practiced, there has been essentially no adoption of conservation/zero tillage for wheat in both developed and developing countries, even though approximately 42% of the wheat produced in developing countries is irrigated largely by gravity irrigation delivery systems (CIMMYT 1989). This is mainly due, in my opinion, to the belief by most researchers and farmers that zero tillage is mainly a practice to be implemented for erosion control and moisture conservation, which represent minor problems in most irrigated production systems. In fact, the need for total or even partial retention of crop residues as a requirement to implement sound zero-tillage can be somewhat relaxed for most gravity-irrigated situations, since the potential role that crop residues will play will be less for erosion control and moisture conservation, and more for soil improvement.

This paper gives most emphasis to characterizing zero-till planting systems and describes potential constraints to their adoption by small farmers. Suggestions to resolve these constraints are given, as well as a description of CIMMYT's efforts to develop a bed-planting system that provides unique opportunities to reduce tillage and manage crop residues in both rainfed and gravity-irrigated cropping systems.

Characteristics and adoption of conservation tillage systems

Phillips (1984) summarized a series of potential advantages of zero tillage planting systems, listed in Table 1. Obviously the list is not complete but illustrates what most successful practitioners of zero-till have encountered: 1) erosion can be dramatically reduced when zero-till is combined with proper crop residue management; 2) moisture conservation is normally improved in low precipitation, rainfed conditions; 3) crop turn-around times are reduced; 4) soil characteristics are improved; and 5) in many cases, production costs are reduced.

The same author summarized the potential disadvantages of zero tillage planting systems (Table 2) (Phillips 1984). Clearly the most important potential problem or disadvantage for farmers who shift from conventional to zero tillage planting involves possible changes in incidence and severity of weeds, insects, disease pathogens, and rodents; important as well is that farmers need to have an appreciation and understanding of "knowledge-intensive" solutions to make zero tillage work. The above authors did not mention another potential disadvantage of zero-till planting systems, which is the tendency for surface compaction to occur in some soils/cropping systems if controlled traffic lanes are not used to restrict machinery traffic in the field (Bolaños 1991).

Table 3 indicates the steady increase in the adoption of conservation tillage in general and in the specific category of zero tillage for several countries and regions in 1990-1995 and gives an estimate for the year 2000. Table 4 presents estimates made in 1995 for the use of zero tillage in several countries and regions. Clearly the developing countries that have made great strides in the use of zero-tillage have been Brazil and Argentina, both characterized by having extensive areas of rather large-scale, mechanized agriculture. Recent estimates indicate that Brazil alone now has over 6 million ha under zero-till planting systems.

The availability of data on the use of conservation or zero tillage by small farmers in developing countries is extremely limited. However, Wall (1998) provides estimates for the use of zero tillage by small farmers in several countries/regions which readily indicate the very low or essentially non-adoption of zero-till planting systems by these farmers. It is not clear, however, if these estimates include the traditional practice, still fairly commonly used by small farmers in Mexico and Central America, of dibble-planting maize and beans into untilled, sloping lands where crop and weed residues have been hand-chopped and left on the surface; or similarly, the traditional practice, used by small farmers in south Asia, who broadcast seeds of pulse and oilseed crops into the standing or recently harvested rice crop located in lowland, mainly rainfed, rice fields, using what must be the simplest zero-till planting system.

CIMMYT, as well as many other national and international institutions, are now placing a high priority on developing appropriate conservation/zero tillage technologies to extend to small farmers. Table 6 provides a list of CIMMYT agronomists currently involved in this activity, their locations, and their addresses.

Constraints to the adoption of zero-till by small wheat farmers

Table 7 lists some major reasons for the lack of adoption of zero-till planting systems by small wheat-producing farmers in developing countries. They are briefly discussed below.

Lack of appropriate small-scale planters

Probably the most crucial factor limiting small farmer use of zero tillage is simply the lack of appropriate, small-scale planters (especially for wheat) that can be used with draft animals or small 2- or 4-wheel tractors. Such planters must be small, yet able to penetrate untilled soil to both place and cover the seed, usually through variable amounts of crop residues on the surface, and this causes difficult design issues. The requirements for zero-till planters suitable for row-planted crops like maize or soybean which have between-row spacings normally ranging from 60-100 cm are more readily resolved. Such prototype planters for use with draft animals have been developed in several countries. One such planter is being commercially manufactured and distributed in Brazil, where it is being used by increasing numbers of small farmers to plant by zero tillage maize and soybean as well as other row crops (Wall 1998).

Progress in developing small-scale, zero-till wheat planters has been much slower, mainly because of the narrower row-spacings (10-30 cm) used for wheat. Designing a small-scale planter that can plant several rows (at least 2-4) in one pass into untilled soil through surface residues and be pulled by draft animals has proven to be a challenge. Some attempts have been made to use the single-row zero-till planters described above to plant wheat but making multiple, close passes to obtain close-seeded rows of wheat has proven difficult, especially with draft animals.

The University of Pantanagar, located in the state of Uttar Pradesh in India, has made excellent progress in developing a small zero-till planter (planting 6-10 rows) that can be used with small horsepower, 4-wheel tractors but not, as yet, with draft animals. The planter has been used mainly to seed wheat zero-till following flooded rice under conditions where a long turnaround time for preparing land for wheat is common after harvest of the transplanted rice crop. Delay in planting wheat past the optimum date (around mid-November) in northwest India and Pakistan leads to dramatic yield reductions, as seen in Figure 1. Therefore the time that can be saved by planting wheat zero-till is of utmost importance in that region, as well as in south Asia and China, where the rice-wheat rotation is widely followed. Likewise, zero-till planting could be used to reduce turnaround time for wheat planted in rotation with other summer crops such as cotton, soybean, and maize in the same region.

The main drawback of the Patanagar zero-till seeder is that, as currently designed, it cannot handle seeding into high levels of crop residues (most farmers currently remove almost all the rice straw) but simple modifications can be made to allow zero-till planting into residues. The planter's soil opener design (based on the inverted T shank) and seed and fertilizer delivery system could serve as models for smaller zero-till planters that could be used with 2-wheel tractors or draft animals.

Researchers in several countries of south Asia have also been developing technologies for "surface seeding" wheat. Surface seeding is similar to the previously described practice (common in the region) of relay-planting pulses or oilseeds into the standing rice crop. Pre-germinated wheat seed is broadcast into rice soon before or just after the rice harvest. The technique works best on finely textured soils when soil moisture content is near saturation but there is no standing water. Farmer field trials using surface seeding in Nepal have clearly demonstrated dramatic reductions in wheat production costs, increased wheat yields, and better wheat quality. This is the result of planting 15-25 days earlier, which is possible with surface seeding because it eliminates the need to wait for the soils to dry-down sufficiently to permit tillage and subsequent planting (Hobbs *et al.* 1997).

Another innovation in south Asia is the work being done by CIMMYT scientists Peter Hobbs and Scott Justice in Nepal and Craig Meisner in Bangladesh (see Table 6), along with their national program colleagues, to adapt the versatile 2-wheel Chinese tractor for either zero-till or one-pass reduced-till planting of wheat after rice (Hobbs *et al.* 1997). The potential role that these low-cost, 2-wheel tractors may have for small farmers in developing countries for tilling, planting, hauling, pumping water, driving small threshers, etc., is tremendous, and explains their rapid adoption outside of China, in Bangladesh and Nepal. The 2-wheel Chinese tractor should be evaluated with small farmers in many other developing countries as a potential "next-step technology" to provide a more direct avenue to implement conservation/zero tillage as well as to improve labor-use efficiency.

Problems related to crop residue management

There are several, somewhat contrasting constraints associated with crop residue management that inhibit small farmer adoption of zero tillage planting systems.

First, in many cases, sufficient crop residues are not left on the soil surface. Many small farmers remove all crop residues for either animal fodder and/or fuel. Furthermore, in many dryland, non-irrigated areas where rainfall is low and quite variable, the total amount of crop residues at harvest may be very reduced and variable (perhaps too little to provide adequate ground cover) because of the direct association between residue yields and low crop yields. In most situations, farmers who convert to zero tillage, but continue to remove crop residues for feed/fuel or obtain very low residue yields, will usually produce lower yields than with conventional tillage practices. This is especially true in low rainfall, dryland areas or where conditions are conducive to severe wind or water erosion.

This premise is fully supported by the results of a long-term trial being conducted under rainfed conditions at El Batan, Mexico (CIMMYT Headquarters), in which wheat and maize are grown continuously as monocrops or in rotation (one crop per year), with zero or conventional tillage and with all residues retained or removed.

Table 8 presents the wheat and maize yields for the various treatment combinations used in this trial averaged over the 1996 and 1997 crop cycles (see Appendix 1 for individual crop cycle yields and the ANOVA over both crop cycles for both crops). It appears obvious that for either continuous or rotated maize or wheat, when zero tillage was used combined with crop residue removal, yields were consistently lower than when residue was retained. Furthermore, in most cases, the zero-till yields for either crop—regardless of rotation—were also lower than when conventional tillage with residue removal was practiced (this is more clearly illustrated by the residue management/tillage means given in Table 9).

A good rule of thumb is that zero-tillage should probably not be implemented if it is not possible to maintain sufficient residues for adequate ground cover, especially under erosion-prone, low-but-intense-rainfall, dryland conditions. However, much research is needed to determine adequate or "threshhold" levels of residues for each soil, topographic, climatic, and cropping system situation. For example, can small farmers remove the top part of the maize plant (from just below the ear) or cut wheat to a certain stubble height to provide a substantial part of their fodder requirement yet leave enough residue in the field for satisfactory zero-till planting? Answers to such questions are needed to provide guidelines to small farmers for proper implementation of zero tillage practices.

Second, in most irrigated high-yield environments (and for many high rainfall, rainfed conditions), a contrasting situation is often the case: too much crop residue is produced, which may lead to zero-till management problems. This has been one of the prime factors inhibiting the use of zero tillage with residue retention in surface-irrigated, wheat-based cropping systems, except where most residues are physically removed for fodder or other purposes, or burned (if no economical use of the residues is available). Residue removal is currently practiced by farmers using the Pantanagar zero-till planter in the rice-wheat rotation in India.

Rice straw yields from high yielding, irrigated rice crops in south Asia can reach 6-10 t/ha; wheat straw yields can range between 5-9 t/ha. In the irrigated, wheat-maize rotation in the Yaqui Valley in the state of Sonora in northwest Mexico, wheat straw yields can reach 6-10 t/ha and maize stover yields 8-12 t/ha (Sayre and Moreno 1997). In all these cases, crop residue levels can cause problems in designing zero-till soil openers that could successfully: 1) pass through the field without plugging or dragging residue (especially for zero-till wheat planters with their normal, close row-spacing); 2) place the seed into the untilled soil at the proper depth without pushing uncut residue (called hairpinning) into the seed slot; and 3) achieve proper, uniform seed coverage and optimum soil contact. In addition, under flood irrigation conditions, the presence of residue can dramatically interfere with the efficient movement of irrigation water through the field.

Third, to facilitate an efficient, uniform zero-till planting operation, the retained crop residues must be chopped and uniformly distributed. Large, mechanized farmers who have adopted zero-till perform these activities by attaching to their combines straw choppers that both chop and spread the residue or by using tractor, PTO-powered flail or rotary choppers after harvest. These options are largely beyond the reach of most small farmers, especially those who hand-harvest (wheat, for example) and remove the bundles from the field to be threshed elsewhere or even those who harvest in the field (maize, for example) and leave all or part of the residues *in situ*.

The first situation is probably the most difficult to resolve. If the farmer hand-harvests and removes a major part of the crop residue to thresh the grain outside the field, the logical solution is to return the residue and distribute it evenly over the field. This is obviously labor intensive, and its feasibility may depend upon the farm-level benefits that may be obtained from zero-till planting if the residue is returned to the field. Removing wheat straw at harvest and later returning it to the field (usually following composting) is commonly practiced by many small farmers in China to maintain soil productivity. Though in this case conventional tillage is used, the example illustrates that returning residue to the field, whether as compost for more sustainable production with conventional tillage or to provide adequate ground cover for zero-till, may be feasible for small-scale farmers.

In the second situation, where the crop is harvested in the field by hand or machine and the residues are left in place, some method is needed for chopping the residue that preferably does not involve high-powered machinery. The Brazilians have developed a knife-roller (*rolo-faja* in Brazil) that is being used by both small and large farmers. The knife-roller is made by placing an axle through a drum, allowing the drum to rotate, (the drum may be no more than a meter wide for small-scale models) and then filling the drum with sand (or even water, if the drum is well-sealed) to provide weight. Knife blades the width of the drum are attached at regular intervals around the drum. The blades cut the residues (length of cut is determined by the space between the knife blades) as the drum is rolled, pulled through the field by draft animals or by 2- or 4-wheel tractors. The knife-roller can be readily made by local blacksmiths or machine shops and meets most requirements for implementation by small farmers.

Finally, a common and frustrating situation is uncontrolled community grazing, where farmers simply release their livestock to graze freely throughout the surrounding area, especially during the dry off-season, in one-crop-per-year locations. Some farmers retain crop residues in their fields to enable them to implement effective zero-till planting only to find that their neighbors' livestock have grazed-off the residue.

Fencing-in the fields is one solution, albeit usually expensive, often beyond the economic reach of small farmers and usually does not provide complete protection. Another solution is the organization of the community's commitment to control free-grazing with realistic and enforceable penalties against those who do not participate.

Problems associated with fertilizer management

Fertilizer management in zero tillage systems obviously varies over the myriad production systems in terms of which sources to apply and how, when, and where they should be applied to achieve the most efficient utilization. It is clear that nitrogen (usually the most widely used and most costly fertilizer, and the nutrient most easily subject to loss) requires the most attention by farmers practicing zero tillage and that it has received more research attention.

Selecting the source of N fertilizer is important especially if surface broadcasting is to be used. The possibility of losses through volatization can be quite high when N fertilizer is surface broadcast into crop residues, especially if urea is used. Ammonium nitrate is a more appropriate source because it is not subject to volatization losses (Thomas and Frye 1984). In addition, when N fertilizer is surface broadcast into heavy layers of crop residue, surface microbes can tie up a substantial amount of the applied N for varying periods of time (Domitruk and Crabtree 1997).

Most zero-till farmers prefer to apply a part or all of the N (and in some cases P and K) mechanically by band placement into the soil at planting, usually followed by a second application in the same manner when the applied N is divided. Band placement of N into the soil through the residue can markedly improve N-use efficiency compared to surface broadcasting (Domitruk and Crabtree 1997). Band application at planting is feasible for essentially all crops including wheat when appropriate zero-till planters are available. However, the ability to both plant and band fertilizer introduces another design requirement that may constrain the development of small-scale zero-till planters for small farmers (especially for wheat). In addition, a second, mechanized, direct-band application in normal, narrow-row-spaced wheat is extremely difficult to do without damaging the crop. Therefore, farmers who want to produce zero-till wheat (both large- and small-scale) and who also want to do a second, split application of N will likely need to rely on some manner of broadcast application. In those cases, fertilizer source and conditions at the time of application will be of utmost importance to enhance N-uptake efficiency.

The management of P and K as well as other, less mobile nutrients in zero-till planting systems is somewhat less complex than managing N and S, which are more mobile and more easily lost through improper management. Surface broadcasting of low-mobile nutrients like P and K can result in their stratification, over time, near the soil surface. This may not be a problem except when the surface soil layer where they are concentrated becomes so dry that active uptake by roots is inhibited (Domitruk and Crabtree 1997). The most efficient way to manage the less-mobile nutrients in most situations may also be by direct band placement near the seed at planting, but this may further complicate designing small-scale, zero-till wheat planters.

Finally, there has been very little research on how to efficiently manage sources of farmyard manure in zero-till systems. A trial with irrigated wheat planted using zero-till on permanent beds was conducted at the CIANO experiment station in the Yaqui Valley, Sonora, Mexico, during the 1995/96 crop cycle. One of the treatments was chicken manure broadcast on the soil surface just prior to planting to provide 180 kg N/ha. Other treatments involved different rates of

N applied just prior to planting as surface-applied urea for comparison. The treatment receiving the 180 kg N/ha as chicken manure yielded 5110 kg/ha and the treatment that received 150 kg N/ha as urea yielded 5500, indicating that N-use efficiency with the manure treatment was only slightly less than with urea.

Potential weed, disease, and insect problems

Most zero-till practitioners have discovered that the key to minimizing potential problems associated with weeds, diseases, and insects is crop rotation. In the case of diseases and insects, this means primarily crop rotation using varieties with disease or insect resistance, if available. Minimizing weed problems also implies using crop rotations and, in addition, rotating herbicides associated with normal weed control for the different rotated crops as well as the conscious use of different herbicides, over time, on any given crop in the rotation. The fact that most zero-till systems rely more heavily on chemical weed control than many conventional tillage systems may hinder small farmer adoption, given the problems associated with herbicide costs and availability, the scarcity of and cost of application equipment, and the potential lack of proper application knowledge and information (Domitruk and Crabtree 1997).

Obviously, the importance of crop rotations in most crop production systems is well known, regardless of tillage practice; however, since the retained crop residues required for most zero-till systems can harbor diseases and insects that may use them as a bridge from one crop cycle to the next, crop rotations are essential for most zero-till environments.

Farmers in Brazil currently plant more than 6 million ha by zero-till. However, very early on they realized they could not practice the common soybean-wheat or maize-wheat rotations with zero tillage that had been used for so many years with conventional tillage (and which had led to severe erosion). The soybean-wheat rotation did not provide enough durable crop residues, especially after soybeans grown during the hot, humid summer, to control erosion during the following, cooler season. Maize or sorghum had to be included in the rotation (with the grain harvested) but also to provide a better source of crop residues more resistant to rapid breakdown. In some cases, cover crops like black oats (*Avena strigosa*) were added to the rotation, purely to be chopped soon after heading and left on the surface as ground cover (Fernandes *et al.* 1991).

The wheat-maize rotation under zero-tillage provided sufficient residue for ground cover to guard against erosion in most cases, but these same residues led to extensive foliar blights in wheat and *Fusarium* problems in both maize and wheat. Additional rotation crops including soybean, canola (*Brassica* sp.), and black oats were added to help reduce disease carryover by the surface-exposed maize and wheat residues (Fernandes *et al.* 1991).

If modifying the crop rotation is essential to minimize the negative impact of weeds, diseases, and insects caused by changing to zero-till systems, any factor (economic or otherwise) that interferes with this crop diversification will almost certainly constrain the adoption of zero-tillage by both small- and large-scale farmers. In different parts of the world, farmers have recently shifted to zero-till planting with residue retention yet have continued to grow maize and small grains in rotation. The problems associated with *Fusarium* in all crops have led to tremendous economic losses and farmer disappointment with zero-till.

Alternatives offered by bed-planting systems for wheat

The previous sections of this paper have attempted to emphasize the potential benefits of conservation/zero tillage systems and yet not overlook the obvious constraints inhibiting adoption by small farmers. Specific factors believed to hinder adoption by small farmers have been presented along with some suggested solutions. Without a doubt, modern zero tillage is primarily a mechanized technology for large-scale farmers and could remain so if innovative thinking and actions are not brought forward. We may be somewhat short-sighted if we simply rely on attempts to "scale-down" what large, zero-till farmers are now doing, although their experiences and equipment designs certainly will be (and already are) useful in many cases. However, small-scale producers, especially of wheat, who use zero tillage are still few and far between.

To address this issue, about seven years ago the CIMMYT wheat agronomy group initiated research to determine whether planting wheat on permanent beds might offer new, alternative approaches to solve some of the constraints that hinder small farmer adoption of conservation tillage practices.

Planting wheat (and other crops, for that matter) on beds with conventional tillage is not new in areas where surface irrigation using the furrows between the beds to deliver irrigation water is practiced. For row crops such as maize, cotton, sorghum or soybeans, usually one row of the crop is planted on the top center of each bed. However. in these areas wheat is normally planted by drilling or broadcasting the seed on the flat, tilled soil followed by formation of the furrows (usually 70-100 cm apart) for subsequent irrigation.

Wheat planting on beds, however, has been dramatically changed by researchers and farmers in northwest Mexico over the past 20 years. Farmers in this irrigated region plant wheat on beds prepared before or at planting that are 70-100 cm wide (from center bed to center bed) by seeding 2-4 rows on top of each bed spaced 15-30 cm apart. No wheat is planted in the furrows between the beds, which are used to apply irrigation water. The bed width chosen by farmers for wheat is compatible with the requirements for other crops in their rotations (mainly maize, cotton, safflower, sorghum, and soybean) to ensure machinery compatibility between crops (Sayre and Moreno 1997). The innovative placement of a defined number of rows of wheat on top of the beds combined with the fact that over 90% of the farmers in the region have adopted the system stimulated the current effort at CIMMYT aimed at investigating the potential for bed-planting systems to extend to other parts of the world.

Figure 2 summarizes our current thinking on the possible uses of bed-planting systems. Though most farmers in northwest Mexico who plant on beds use irrigation and conventional tillage, our research has clearly shown that bed-planting of wheat and other crops can be applied in rainfed conditions and can provide opportunities to reduce tillage dramatically through the use of permanent beds. Emphasis here will be on discussing the use of permanent beds for either rainfed or irrigated conditions.

One fact that has been constant throughout our work on bed-planting wheat is that not all available wheat varieties will perform well on beds. Some varieties may perform very well when planted conventionally in narrow rows on the flat, but not on beds. Other varieties perform well under both planting systems. Table 10 presents the results of a trial carried out under irrigation in northwest Mexico with eight bread wheat varieties that clearly illustrates this. A crucial first step in initiating research on bed-planting wheat is to test a wide spectrum of varieties with differing heights, tillering abilities, phenologies, and canopy architectures. Close cooperation between wheat breeders and agronomists to jointly identify and understand the proper plant type needed for optimum performance on beds is highly recommended.

Table 11 presents a list of potential advantages of permanent bed-planting that includes both farmers' reasons for adopting beds (compiled from survey information in Mexico) and observations from our research results. Most are self-explanatory, but some are discussed in more detail within a brief description of relevant results of our on-going research.

Permanent beds are initiated using a conventional tillage that allows well-formed beds to be made and the initial crop planted. Subsequently, no additional tillage is used except to reshape the beds as required, by passing a winged-shovel in the furrow (usually before planting each crop but may be less often depending on crop and soil type). No tillage is made on the top of the bed except that associated with planting. If crop residues are chopped and retained, a cutting-disc may need to be placed ahead of the reshaping shovel to allow its free passage through the furrow without clogging with residue during the simple bed-reshaping process (this same equipment can be used for mechanical weed control when feasible).

The appropriate bed width must be carefully determined, especially when permanent beds are being established. Major considerations are: 1) compatibility for the various crops to be grown in rotation and 2) compatibility with planting and bed-reshaping equipment. We have found that keeping the bed width at 70-100 cm allows maximum flexibility for field access by farmers and makes the design of small scale planting and bed-reshaping equipment for use with draft animals or 2-wheel tractors more feasible. In our experience wider beds (1.5-2.5 m) are difficult to use with existing equipment for efficient planting and weed control, especially in small-scale applications.

In 1992 a trial was initiated at CIMMYT's station in northwest Mexico to study the long-term effects of permanent beds (with bed re-formation before planting each crop as the only tillage) for planting wheat and maize in rotation under irrigation. The trial included different crop residue and N management strategies.

Table 12 presents the average wheat yields for the five crop cycles (1993-1997). All permanent bed treatments gave higher yields than conventional tillage (where beds were destroyed by tillage after harvest and remade–the common farmer practice) with best performance where all crop residues were retained (although similar to the permanent bed treatment with all residues burned). These results clearly show the potential for this system to finally provide farmers growing wheat under irrigation with a feasible technology to reduce tillage, retain crop residues, and still use gravity irrigation in the furrows.

This trial has provided information to illustrate that several soil quality indicators have improved over the five-year period. Figure 3 compares the effect of tillage and crop residue management on soil aggregate size. Larger soil aggregate size usually indicates better soil physical status. The largest mean aggregate size occurred with permanent beds and full residue retention, and the smallest size where continuous burning has been practiced (residue burning is the most common farmer practice in the area). Conventional tillage with residue incorporation (the baseline check treatment) had an intermediate mean aggregate size.

Figure 4 compares levels of soil microbial biomass (SMB) at two depths for the same treatments shown in Figure 3. Dramatically lower levels were seen where residues were burned, especially in the 7-15 cm profile. The other treatments had similar total SMB levels but marked differences for the two depth profiles. Both Figures 3 and 4 support the assumption that permanent beds with residue retention can lead to significant improvements in soil quality indicators, as has been found in other conservation tillage systems (Phillips and Phillips 1984).

Permanent beds offer new degrees of freedom to farmers in terms of field access. The furrows between beds provide a built-in system to control machine, human, and draft animal traffic. Farmers in Mexico (and we in our research) restrict all traffic to the furrows, abating compaction on top of the bed where seeding occurs.

Enhanced field access has important implications for weed control, since farmers can practice mechanical weed control between the beds (a new alternative for wheat) or use the furrows to apply herbicide over a wide range of crop development stages without physically damaging the crop by trampling. In addition, the furrows offer an opportunity to use a much broader spectrum of herbicides than can be applied over the top of the wheat crop by later season directed applications in the furrows, with cone-protectors when needed. In addition, hand weeding wheat is more efficient because the defined row orientation on the beds allows easier identification of grass weeds and easier access and removal.

But perhaps the most important field-access advantage for wheat is the flexibility bed-planting provides to allow fertilizer placement where and when it can be most efficiently used. Fertilizer, especially N fertilizers, can be applied by direct placement in bands in between the wheat beds or rows when the wheat plant can make most efficient use without trampling the crop. A decision can be made to delay the bulk of applied N fertilizer until after the crop is up and growing (without having to rely on more risky broadcast application) when more decision-making information to judge N requirement is available compared to before planting.

Figure 5 shows yield results for a trial where two N rates were applied either as basal application (banded into the bed) at planting or at the 1st node stage (banded 35 days after crop emergence). The zero N check is included for comparison. At the 150 kg N/ha rate, higher yields were obtained with the 1st node application, whereas no timing difference was observed for the 300 kg N/ha rate (probably outside the response range). Figure 6 presents the whole plant; total N-uptake results for the same treatments indicate markedly higher N-uptake levels for the 1st node application at both N rates. These data were used to calculate N-uptake efficiencies for the treatments adjusted for the N taken up in the zero N treatment and are shown in Figure 7. Dramatic increases in N-uptake efficiency for both N rates (especially for 150 kg N/ha) were obtained.

Similar positive results from delaying all or part of the applied N until the 1st node stage have been observed on wheat quality parameters. Figure 8 shows the response in bread wheat loaf volume when a total of 150 kg N/ha is applied (all or part) at different times. Dramatic increases occurred when all or part of the N was applied at 1st node as compared to all applied at planting.

These results show how improvements in N-use efficiency can be achieved by delaying all or part of the N application to around the 1st node stage. Large cost savings to farmers appear possible and, of equal importance, less N may be lost to into the environment through volitization or leaching. The ability of farmers to accomplish this is greatly facilitated by the bed-planting system.

Research to apply permanent beds for rainfed conditions has only just begun at CIMMYT. We are strongly convinced that bed-planting (with or without tillage) offers a very sound method for planting wheat and other crops under high rainfall conditions where excessive moisture can cause waterlogging. The furrows between the beds provide natural drainage channels to rapidly remove the excess water from the field. Bed-planting also can be very effective for drainage where shallow water tables result in excess surface moisture, especially after rain or even with irrigation.

Under low rainfall conditions where moisture is limiting, our initial results demonstrate that moisture can be effectively conserved with proper residue retention and management (residues are concentrated in the furrow bottoms) on permanent beds. Furthermore, where conditions allow, small dams can be placed at regular intervals in the furrows (commonly referred to as tied ridges) at a height slightly lower than the top of the bed to allow drainage if excess moisture is present; this helps prevent excessive rain run-off. We are finding that this technique can efficiently conserve moisture with only minimal retention of crop residues, thereby providing another valuable technology that allows a small farmer to reduce tillage, conserve moisture, and use a major part of the crop residue for fodder. Considerable new efforts are underway at CIMMYT to explore the application of permanent beds to wheat-based rainfed production systems.

Conclusions

Small farmers have been largely by-passed by the rapid adoption of conservation/zero tillage planting systems that is occurring in many parts of the world. Currently, most available equipment to implement these technologies is too large for use by small farmers. Researchers have tended to ignore the potential application of conservation/zero tillage by small-scale farmers, but this is beginning to change, especially in developing countries, where the vast majority of small farmers live and work.

Genuine constraints do exist that inhibit the realistic development of appropriate technologies, but they are not insurmountable if researcher common sense is combined with farmer knowledge and participation in the development process. Work on wheat bed-planting systems at CIMMYT, which strives to combine the remarkable flexibilities and alternatives provided by the method (characteristics so much needed and appreciated by farmers) with the potential to markedly reduce tillage and to properly manage crop residues in both irrigated and rainfed conditions, is hopefully a step in the right direction.

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Table 1. Potential advantages of zero tillage planting systems.[a]

- Reduced erosion.
- Reduced production costs.
- Improved crop turnaround times.
- Increased land-use efficiency.
- Improved water use.
- Improved soil physical, chemical, and biological characteristics.

[a] Adapted from Phillips and Phillips, 1984.

Table 2. Potential disadvantages of zero tillage planting systems.[a]

- Reduced soil temperatures during cool periods lead to stand establishment problems.
- Weed control may be more problematic.
- Disease, insect, and rodent incidence may change/increase.
- Aesthetics of field difficult for some farmers to accept.

[a] Adapted from Phillips and Phillips, 1984.

Table 3. Percent of agricultural land under conservation tillage (including zero-tillage) and zero-tillage alone in the USA, Canada, South America, Western Europe, and Australia.

Year	% Conservation tillage	% Zero tillage
1990	9.8	2.3
1991	10.5	3.5
1992	13.6	5.2
1993	16.0	7.1
1994	18.3	8.7
1995	22.0	10.8
2000 (estimated)	28.0	14.0

- Excludes: Eastern Europe, the former Soviet Union, Africa, and Asia.
- Adapted from Alesli, 1996.

Table 4. Estimated crop area under zero tillage planting systems in 1995.

Country/region	Area (million ha)
USA	16.4
Canada	5.5
Brazil/Argentina	8.1
Western Europe/Australia	2.0
Total	32.0

- Adapted from Alesli, 1996.

Table 5. Estimated area planted with zero-tillage and crop residue retention by small farmers.[a]

Region	Area (ha)
Southern Cone of South America	25,000
India, Bangladesh, Nepal[b]	10,000
Mexico and Central America	<10,000
China	minor
Southern Africa	minor
West Africa	minor
East Africa	very minor
Andean Region	very minor

[a] Adapted from Wall, 1998.
[b] May not include pulse crops relay planted by broadcasting seed into the standing or recently harvested rice crop under lowland, rainfed conditions.

Table 6. CIMMYT agronomists involved in reduced/zero tillage research and related small-scale equipment evaluation and development.

Scientist	Region/country of assignment	Mailing address and e-mail	Research focus
Pat Wall	Bolivia (provides linkages with other South American countries)	CIMMYT c/o ANAPO Casilla 2305 Santa Cruz, Bolivia cimmyt@bibosi.scz.entelnet.bo	Reduced and zero tillage/seeding with residue management. Rainfed wheat-based system for both the small farmers in mountain valleys and hill-sides and the mechanized eastern plains of Bolivia. Actively evaluating, modifying and developing small and moderate scale zero-till planting equipment.
Douglas Tanner	East Africa with base in Ethiopia	CIMMYT P.O. Box 5689 Addis Ababa, Ethiopia cimmyt-ethiopia@cgnet.com w.mwangi@cgnet.com	Conventional, reduced-till, zero-till and raised-bed seeding systems with residue management for rainfed wheat based systems. Small farmer emphasis and investigating small scale planters and weed control equipment.
Peter Hobbs and Scott Justice*	South Asia with base in Nepal	CIMMYT P.O. Box 5186 Lazimpat, Kathmandu, Nepal phobbs@mos.com.np p.hobbs-t@cgnet.com cimkat@mos.com.np *justice@wlink.com.np	Reduced-till, zero-till and raised bed seeding systems in irrigated small farm rice-wheat systems. Emphasis on testing small zero-till and bed-planting seeders for small 4-wheel tractors and application of Chinese 2-wheel tractors with associated tillage and seeding attachments. Testing direct surface seeding of wheat into standing or recently harvested rice.
Craig Meisner	Bangladesh	CIMMYT P.O. Box 6057 Gulshan, Dhaka 1212, Bangladesh cm@cimmyt.bdmail.net	Reduced tillage seeding and direct surface seeding of wheat into standing or recently harvested rice in both rainfed and irrigated rice-wheat systems. Small farmer focus and involved in extension of the use of Chinese 2-wheel tractors.
Ken Sayre	Mexico	CIMMYT Apdo. Postal 6-641 06600 Mexico, D.F. k.sayre@cgnet.com	Bed-planting systems for conventional and reduced (permanent beds) tillage with residue management for both rainfed and irrigated wheat based systems. Developing small scale seeders for bed-planting.
Eric Scopel	Mexico	CIMMYT Apdo. Postal 6-641 06600 Mexico, D.F. 74751.3644@compuserve.com	Reduced and zero tillage planting systems with crop residue management. Focus on small farmers in rainfed maize based systems in sloping, erosive land. Testing small scale reduced and zero-tillage seeders.
Jorge Bolaños	Central America with base in Guatemala	CIMMYT Apdo. Postal 231-A Guatemala cimmyt@ns.guate.net jbolanos@ns.guate.net	Reduced and zero-till seeding in maize-based systems with small farmers in sloping, erosive lands. Crop residue management and use of strategic cover/mulch crops.

Table 7. Main constraints affecting the adoption of zero-tillage planting systems for wheat and other crop by small farmers.

- Lack of appropriate small-scale planters.
- Crop residue management issues:
- Removal of residues for fodder and/or fuel.
    - Inadequate residues in low yield environments.
    - Excess residues in high yield environments.
    - Uncontrolled community grazing of residues.
    - Lack of appropriate small scale equipment to chop and evenly distribute residues.
- Problems associated with fertilizer application/management including both chemical and organic fertilizer sources.
- Potential development of new or intensification of existing weed, disease, or insect problems.

Table 8. Effect of tillage, crop residue management, and crop rotation on mean maize and wheat yields under rainfed conditions at El Batan for the 1996 and 1997 crop cycles.[a]

Management practice	**Wheat yield**	**Maize yield**
Tillage - Residue - Rotation	**(kg/ha at 12% H_2O)**	
Zero - Retain - Continuous maize or wheat	4985a	4894a
Zero - Remove - Continuous maize or wheat	3857bc	2503d
Zero - Retain - Wheat rotated with maize	5082a	5197a
Zero - Remove - Wheat rotated with maize	2781d	4870a
Conv. - Incor. - Continuous maize or wheat	4132bc	3425c
Conv. - Remove - Continuous maize or wheat	3477cd	3753bc
Conv. - Incor. - Wheat rotated with maize	4592ab	3358c
Conv. - Remove - Wheat rotated with maize	3853bc	4031b
Mean	4094	4004

[a] Growing cycle total rainfall: 1996 = 509 mm; 1997 = 436 mm.
Means in columns followed by the same letter are not significantly different by LSD (0.05).

Table 9. Effect of crop residue management and tillage on maize and wheat yields under rainfed conditions at El Batan (average yields for the 1996 and 1997 crop cycles).

Residue and tillage management practices: Rotation	Tillage[a]	Wheat yields (kg/ha at 12% H_2O)	Maize yields (kg/ha at 12% H_2O)
Retain	Zero	5034	5046
Remove	Zero	3319	3687
Retain	Conv.	4362	3392
Remove	Conv.	3665	3892
Mean		4095	4004
LSD (0.05)		814	528

[a] Conv. = Conventional tillage.

Table 10. Comparison of grain yields (kg/ha at 12% H_2O) for conventional planting on the flat vs bed planting at high and low seed rates.

Genotype	Conventional 120 kg/ha	90 cm beds 3 rows/bed 100 kg/ha	90 cm beds 2 rows/bed 50 kg/ha	Genotype mean*
7 Cerros 66	8273	8281	7756	8103
Yecora 70	8177	7688	7434	7766
CIANO 79	8059	7805	7993	7952
Seri 82	9671	9393	8948	9337
Oasis 86	9749	8676	8782	9069
Super Kauz 88	9763	8644	8581	8996
Baviacora 92	9767	9796	9699	9754
WEAVER 'S'	9741	9391	9205	9446
Planting method mean#	9150b	8709a	8550a	8803

Means followed by the same letter do not differ significantly at LSD (0.05).

* LSD (0.05) for genotype means is 398 kg/ha; Interaction LSD (0.05) is 684 kg/ha.

Table 11. Advantages of permanent bed-planting systems for wheat production.

- Facilitates reductions in tillage and provides opportunities for crop residue management in gravity irrigation systems.
- Improves irrigation water management as compared to flood irrigation.
- Can reduce the dependence on crop residue retention under dry, rainfed conditions to conserve rainfall when combined with tied-ridges.
- Provides drainage system, where waterlogging conditions can occur.
- Establishes a defined controlled traffic system by restricting machinery and animals to the furrows eliminating compaction in the seeded area on top of the bed.
- Facilitates field access allowing:
  - ♦ Opportunities for mechanical weed control, thereby reducing herbicide dependence.
  - ♦ Opportunities to band apply nutrients (especially N) when and where they can be most efficiently used.
- Usually allows use of lower seeding rates compared to conventional planting systems.
- Usually reduces crop lodging compared to conventional planting systems.
- Leads to rapid turnaround times between crops when a bed width common to all crops in rotation is used.
- Leads to improvements in chemical, physical, and biological soil characters especially for the untilled surface of the bed.

Table 12. Grain yield (kg/ha at 12% H_2O) for bread wheat produced in a maize-wheat rotation on beds under different tillage, residue management, and N-rates averaged over five crop cycles (1993-1997).

Tillage system[a]		Conv.	Reduced	Reduced	Reduced	Reduced	
Wheat residue management		Incorp.	Burn	Partial[b]	Leave	Leave	
Maize residue management		Incorp.	Burn	Remove[c]	Remove[c]	Leave	
N-Rate - Time of application (kg N/ha)		Grain yield (kg/ha at 12% H_2O)N-rate					Mean
0 N		2,991	3,045	3,051	3,659	3,297	3,209
75 N	Basal	4,089	4,690	4,563	4,469	4,787	4,519
150 N	Basal	5,455	5,776	5,451	5,575	5,621	5,576
225 N	Basal	5,913	6,318	5,951	6,068	6,347	6,120
300 N	Basal	6,195	6,638	6,492	5,903	6,502	6,346
150 N	1st node	5,803	5,960	5,615	5,811	5,911	5,820
300 N	1st node	6,310	6,247	6,398	6,072	6,560	6,317
Tillage/residue mean		5,251	5,525	5,360	5,365	5,574	-

F-test year	0.001
F-test tillage/residue	0.08
F-test N-rate	0.001
LSD (0.05) N-rate	117
F-test year * tillage/residue	0.03
F-test year * N-rate	0.001
F-test tillage/residue * N-rate	0.001
LSD (0.05) tillage/residue * N-rate	262
F-test 3 way interaction	NS
CV%	6.8

[a] Conventional: Full tillage with formation of new beds each crop cycle.
Reduced: Superficial reshaping of existing beds.

[b] Wheat residue passing combine is baled off.

[c] Maize residue taken off by baling.

Appendix 1. Effect of tillage, crop residue management, and crop rotation on maize and wheat yield under rainfed conditions at El Batan during the 1996 and 1997 crop cycles.[a]

Management practice	Wheat yield			Maize yield		
Tillage - Residue - Rotation	**1996**	**1997**	**Mean**	**1996**	**1997**	**Mean**
	(kg/ha at 12% H_2O)			**(kg/ha at 12% H_2O)**		
Zero - Retain - Continuous maize or wheat	4868	5103	4985	3701	6087	4894
Zero - Remove - Continuous maize or wheat	3337	4377	3857	2746	2260	2503
Zero - Retain - Wheat rotated with maize	4959	5204	5082	4189	6205	5197
Zero - Remove - Wheat rotated with maize	2470	3092	2781	3699	6040	4870
Conv. - Incor. - Continuous maize or wheat	3947	4317	4132	3775	3076	3425
Conv. - Remove - Continuous maize or wheat	3757	3197	3477	3487	4019	3753
Conv. - Incor. - Wheat rotated with maize	4859	4325	4592	3812	2904	3358
Conv. - Remove - Wheat rotated with maize	3846	3859	3853	4104	3959	4031
Mean	4005	4184	4094	3689	4319	4004

ANOVA factor	ANOVA wheat	ANOVA maize
F-test year	NS	0.01
F-test management practice	0.001	0.001
F-test year * management	NS	0.001
LSD (0.05) year	-	238 kg/ha
LSD (0.05) management	814 kg/ha	582 kg/ha
LSD (0.05) year * management	-	823 kg/ha
CV%	14.3%	9.4%

[a] Growing cycle total rainfall: 1996 = 509 mm; 1997 = 436 mm.

Figure 1. Effect of planting date on wheat yield, Punjab, Pakistan. (Hobbs *et al.* 1997)

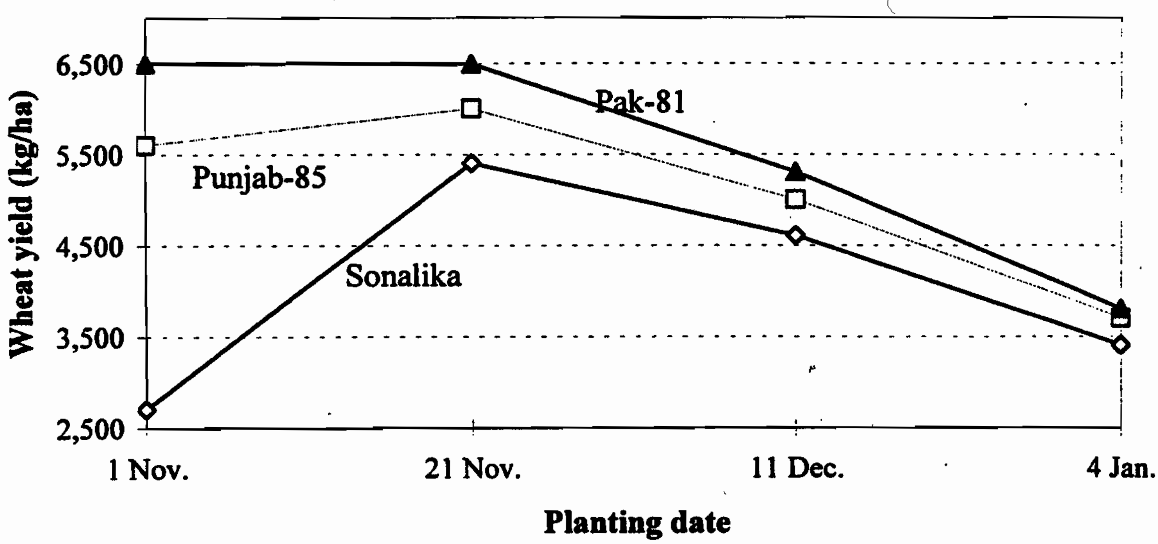


Figure 2. Potential alternatives for bed-planting systems.

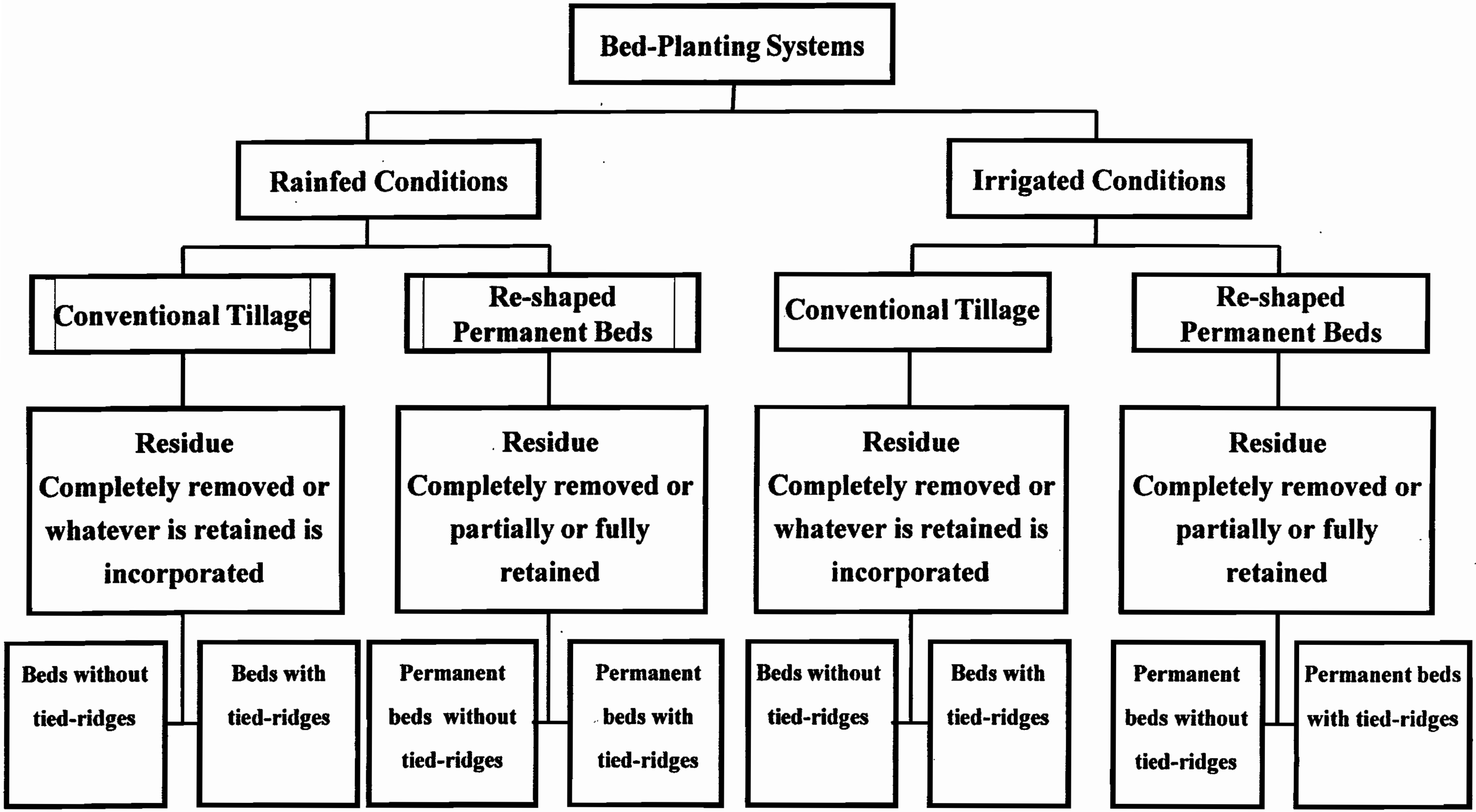
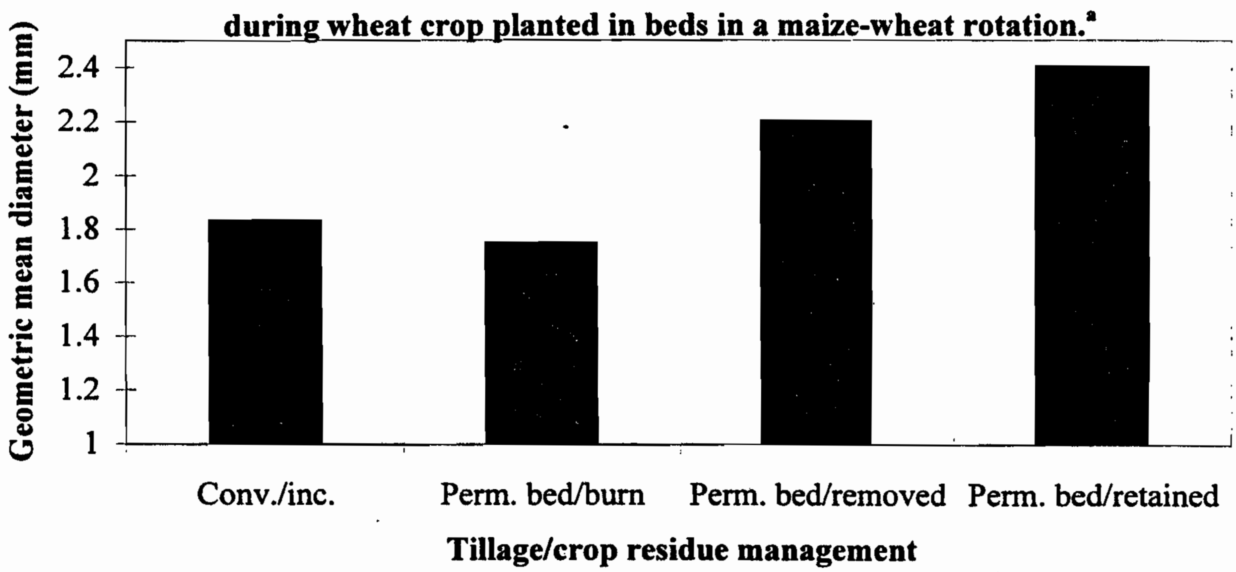
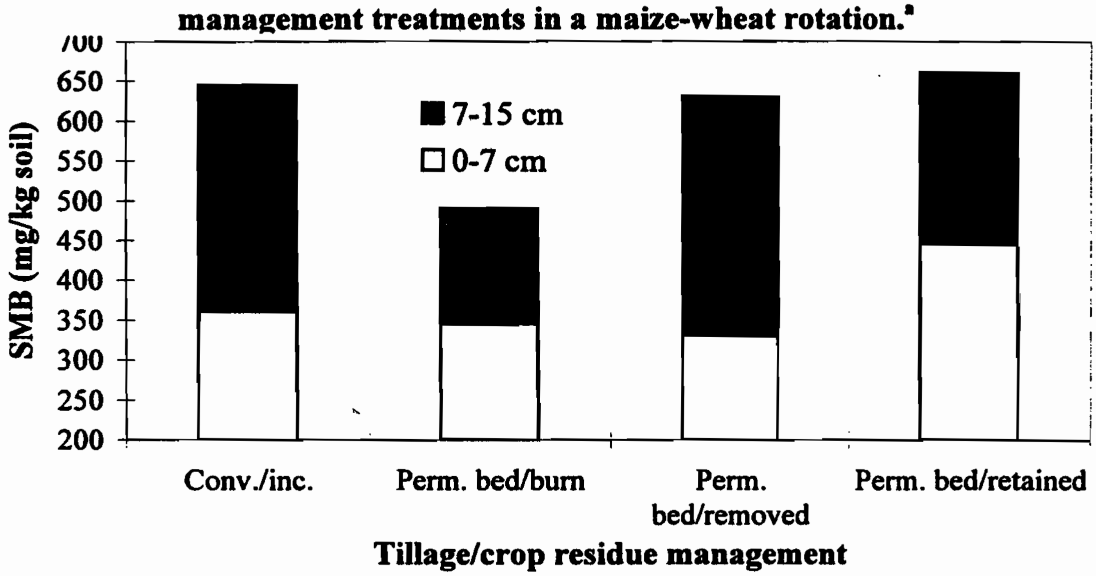


Figure 3. Effect of tillage/crop residue management on soil aggregate size during wheat crop planted in beds in a maize-wheat rotation.[a]



[a] Conv. = conventional tillage; new beds formed each crop cycle. Perm. bed = permanent beds reshaped each crop cycle. Inc. = residue incorporated. Measurements made five years after trial initiated. Data provided by Dr. Agustín Limón.

Figure 4. Soil microbial biomass (SMB) carbon estimated five days after emergence of wheat planted on beds with varying tillage and crop residue management treatments in a maize-wheat rotation.[a]



[a] Conv. = conventional tillage; new beds formed each crop cycle. Perm. bed = permanent beds reshaped each crop cycle. Inc. = residue incorporated. Measurements made five years after trial initiated. Data provided by Dr. Agustín Limón.

Figure 5. Effect of N-rate and time of N application on wheat grain yield.

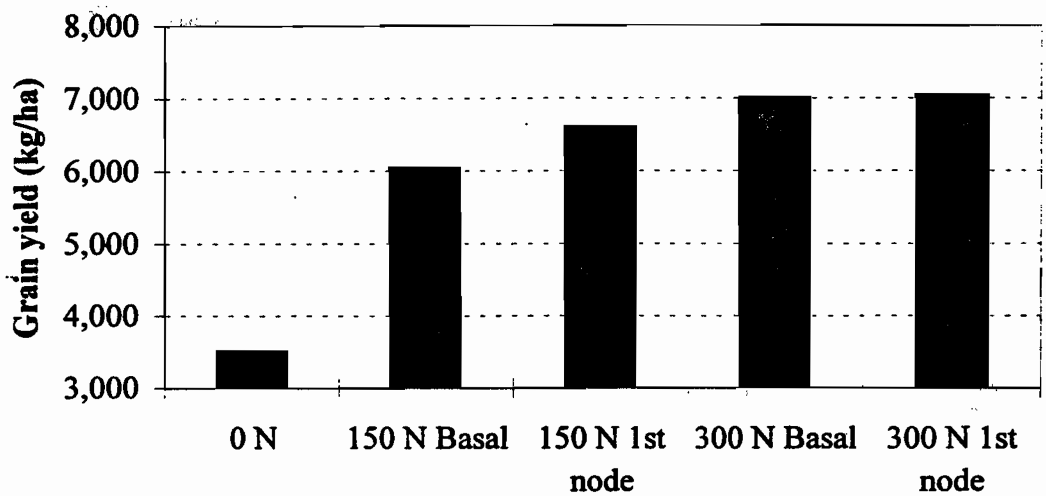


Figure 6. Effect of N-rate and time of N application on whole plant N removal.

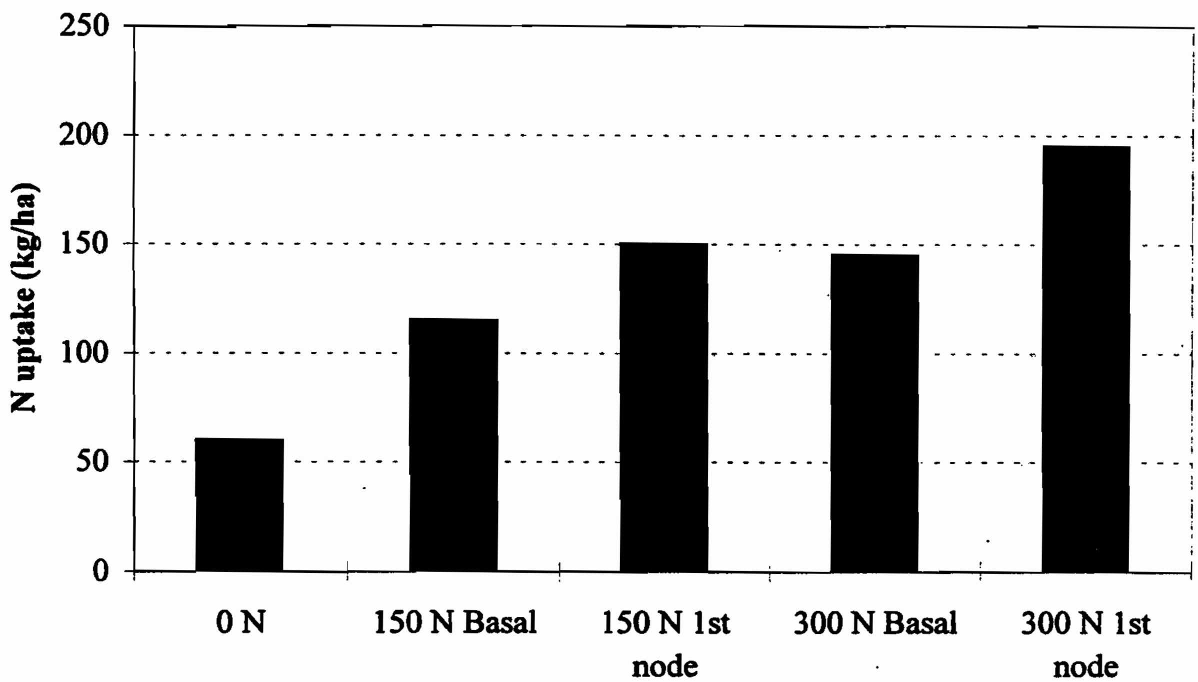
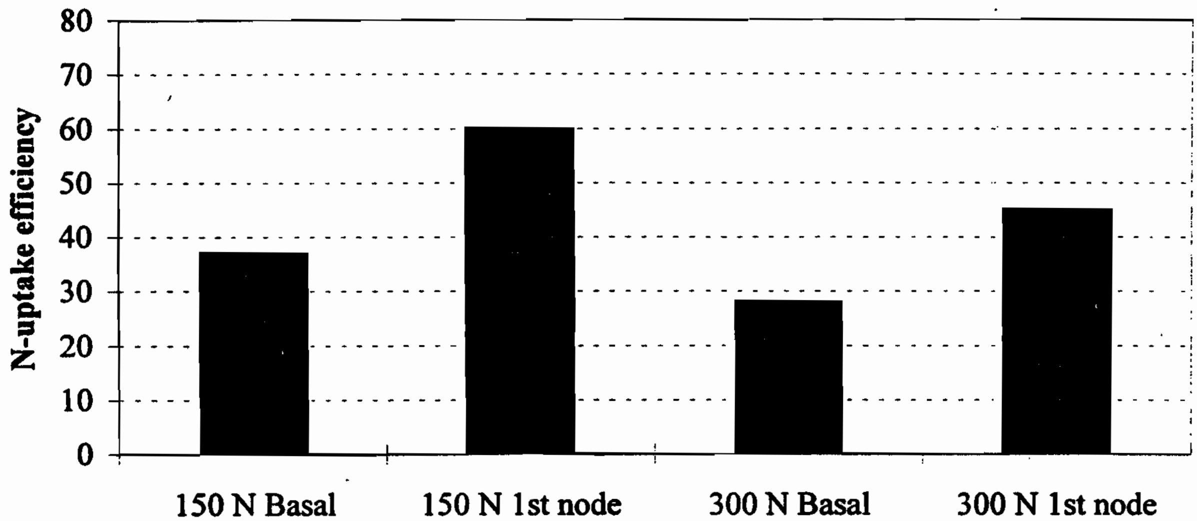
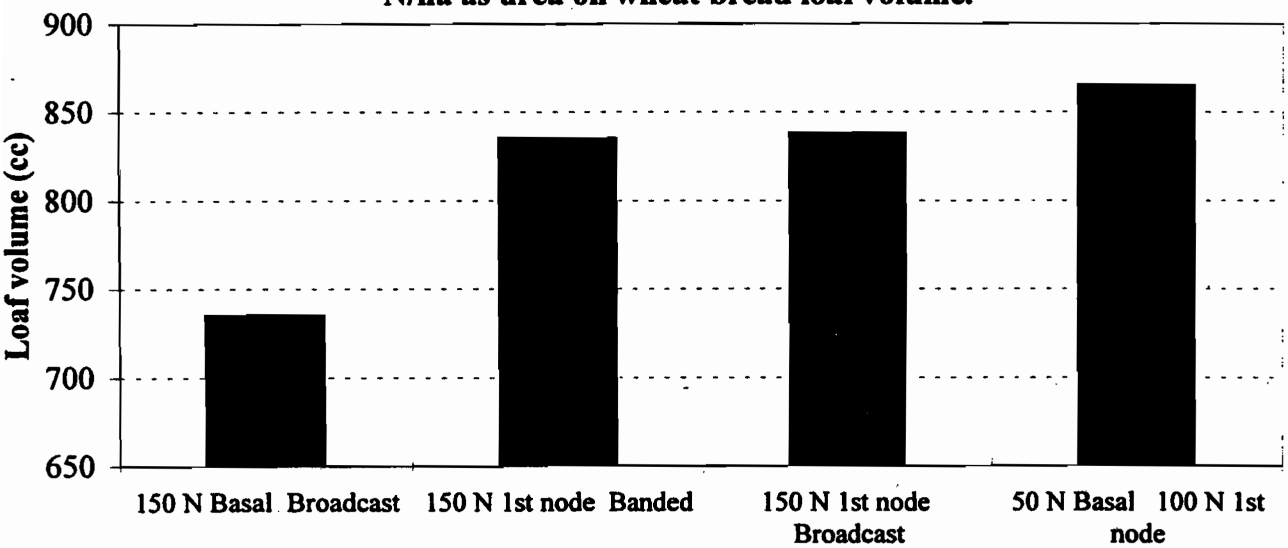


Figure 7. Effect of N-rate and time of N application on N-uptake efficiency.*



$$\text{*N-uptake efficiency} = \frac{\text{(kg N/ha removed at a given N rate - kg N/ha removed at 0 N)}}{\text{N rate}} * 100$$

Figure 8. Effect of different management practices for application of 150 kg N/ha as urea on wheat bread loaf volume.



CIMMYT Wheat Special Reports Completed or in Press

(as of December 1998)

Wheat Special Report No. 1. Burnett, P.A., J. Robinson, B. Skovmand, A. Mujeeb-Kazi, and G.P. Hettel. 1991. Russian Wheat Aphid Research at CIMMYT: Current Status and Future Goals. 27 pages.

Wheat Special Report No. 2. He Zhonghu and Chen Tianyou. 1991. Wheat and Wheat Breeding in China. 14 pages.

Wheat Special Report No. 3. Meisner, C.A. 1992. Impact of Crop Management Research in Bangladesh: Implications of CIMMYT's Involvement Since 1983. 15 pages.

Wheat Special Report No. 4. Nagarajan, S. 1991. Epidemiology of Karnal Bunt of Wheat Incited by *Neovossia indica* and an Attempt to Develop a Disease Prediction System. 69 pages.

Wheat Special Report No. 5. van Ginkel, M., R. Trethowan, and B. Çukadar. 1998 (rev.). A Guide to the CIMMYT Bread Wheat Program. 22 pages.

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