Part 1 Developing No-Till Packages for Small-Scale Farmers

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Introduction

Population and income growth are inducing an intensification of agriculture, which threatens the sustainability of natural resources in rural environments and the livelihoods of small-scale farmers who depend on those resources to survive. Though no single action will reduce poverty and increase the sustainability of agricultural production, technical change can play a prominent role in alleviating these problems. Among the technologies capable of achieving these two goals simultaneously, no-till is one of the most promising in most environments,[1] especially for small-scale farmers.

No-till is sometimes regarded as unsuitable for small-scale farmers, but as this report will show, much evidence indicates that this view is generally untrue. Because it reduces the labor and effort invested in food production, no-till is particularly appropriate for the conditions of small-scale farmers. No-till has been found to cut unit production costs (often up to 50%) and to reduce agricultural risks. Small-scale farmers have used the additional income and time to start new income-generating activities. No-till has also benefited women and children in rural households by facilitating some of the tasks they perform, such as weeding. Living standards rise as families have more money for nutrition, education, and housing. In addition to its economic benefits, no-till confers significant environmental benefits. It substantially reduces erosion and has the potential to diminish pollution from agrochemicals, because of a fall in the volume of chemicals used and a shift to less toxic products. By reducing fuel consumption and conserving organic matter in the soil, no-till reduces the emission of greenhouse gas from agriculture.

No-till is characterized by two profound differences from other agricultural technologies. As this report demonstrates, those differences are extremely important to the potential development and adoption of no-till in small-scale agriculture.

First, no-till represents a major shift in the agricultural paradigm, with consequent implications for researchers and farmers. The old paradigm was based on massive soil disturbance with plows and powerful tractors. The new paradigm, whose best exponent is no-till, is based on three principles: minimizing soil disturbance, covering the soil with plants or plant residues for as long as possible, and rotating crops. Since this technology is very sensitive to environmental conditions, the specific components of no-till packages differ across locations but still share some of the principles mentioned above. Even though packages that reflect all three principles yield the highest long-term economic and environmental benefits, it has been difficult to develop them. Most packages only minimize soil movements and keep the soil covered.

Second, no-till technology is the outcome of a complex social process, and understanding the development

[1] No-till has been developed basically for areas where flood irrigation is not used. Development of no-till or reduced till packages for flood irrigated areas is still in its infancy. Unless otherwise indicated, in the remainder of this report the term no-till refers to packages developed for areas where flood-irrigation is not used (i.e., rain fed or where other irrigation systems are used).

and adoption of no-till requires a new framework for the socioeconomic study of technical change. In the traditional framework, technical change occurs along a continuum that starts with basic research, is followed by adaptive research, and ends with adoption by farmers. Most exchanges of information between the agents involved in technology development and adoption are represented as unidirectional and indirect flows, mediated by markets or printed material. In the new framework, which is based on the concept of "innovation systems," technology development and adoption are social phenomena in which agents interact in several ways, creating multiple information flows in many directions. These agents (e.g., public research and extension systems, innovative farmers, commercial firms, foreign research institutions) form networks that co-evolve with the technologies they create. Just as no-till packages are location-specific, no-till networks and their evolution are also unique. In some cases, as in South America, the main forces driving the innovation system were the commercial interests of input suppliers and commercial farmers' need for sustainable technologies. In other cases, as in the Indo-Gangetic Plains of South Asia, the no-till package was developed through the interaction of researchers in national and international organizations.

No-till has already had a major impact on agriculture throughout the world, but the impact on small-scale agriculture is not always well documented or understood. It is estimated that in 2000/01 about 59 million hectares worldwide were cropped under no-till, mostly by large-scale farmers (Derpsch 2001). A large number of small-scale farmers have also adopted no-till, but because these farmers crop small areas, their adoption of no-till should not be measured in numbers of hectares but in numbers of adopters. Although accurate estimates are lacking, in recent years adoption of no-till has occurred at a rapid pace in several countries. It is estimated that more than 90% of small-scale farmers in southern Brazil use no-till (Denardin and Kochhann 1999); the number of no-till farmers in Ghana in 2000 was estimated at 100,000 (Ekboir, Boa, and Dankyi, forthcoming); and about 100,000 ha of wheat were planted with no-till in India and Pakistan in 2001 (Peter Hobbs, personal communication, 2001). No-till has been promoted in Central America for the last 20 years with localized successes. No-till programs have been established for small-scale farmers in Bolivia, Burkina Faso, Cameroon, Côte d'Ivoire, Ethiopia, Indonesia, Kenya, Malawi, Mali, Mozambique, Paraguay, Senegal, South Africa, Tanzania, Uganda, Zambia, and Zimbabwe, but they are too new to show an impact. Although no-till is also being promoted in China and Kazakhstan,[2] insufficient information is available to evaluate these experiences.

Given its potential to reduce rural poverty and increase the sustainability of agricultural production, especially for farmers with few resources, no-till is particularly relevant to the mission of the International Maize and Wheat Improvement Center (CIMMYT), which has participated in developing no-till technology since the 1970s. Based on an extensive review of experiences with no-till,[3] including CIMMYT's experience, this report explores a number of issues related to the development and adoption of no-till technology, especially in small-scale agriculture. It begins with a description of no-till's special features and the innovation systems through which the technology evolves. As mentioned earlier, a new framework for the socioeconomic study of technical change is needed to understand the development and adoption of no-till. This report describes that framework and reviews the methodological difficulties involved in measuring the benefits and adoption of no-till. This information provides the context for a series of six case studies of no-till experiences among small-scale farmers in Latin America, Africa, and Asia. The concluding sections of the report discuss key factors that condition the effectiveness of no-till programs for small-scale farmers, including the implications for national and international agricultural research.

What Is No-Till?

Because so many terms have been used to describe no-till, it is important at the outset to define what we mean by no-till, to describe some of its benefits, and discuss the factors that encourage and restrict its adoption. Readers who are already familiar with this information may wish to proceed to the next

2 For information on no-till in Kazakhstan, see CIMMYT and ICARDA (2000).
3 Aside from a literature review, more than 150 interviews and field visits were conducted.

section, which reviews the distinguishing features of the no-till research process (p. 8).

Farmers in developing countries have practiced seeding without tillage for centuries. Traditionally, this practice has been associated with slash-and-burn agriculture, in which farmers slash the vegetation on a plot of land, burn the dry residues, and then seed into the uncovered soil. Slash-and-burn agriculture results in rapid soil degradation and is sustainable only when it is associated with shifting cultivation, in which a plot is farmed until its natural fertility declines to the point where it is no longer worth farming it (usually 3-4 years). The farmer then clears a new plot and leaves the degraded plot fallow for a long period (7-10 years) to regain its natural fertility. Increasing population pressure has made less land available for shifting cultivation, forcing farmers in many developing countries to shorten the fallow period. This highly unsustainable practice leads to severe soil erosion and sometimes to desertification and famine.

In modern no-till, the soil remains covered with plant residues (mulch).[4] Several names have been used for this "no-till with mulch" practice: no-till, zero tillage, direct planting, direct planting on residues, and residue conservation. Throughout this report, "no-till with mulch" is referred to simply as "no-till."

More specifically, no-till is defined as planting crops in previously unprepared soil by opening a hole, narrow slot, trench, or band of the smallest width and depth needed to obtain proper coverage of the seed. At least 30% of the soil surface remains covered with residues of commercial or cover crops[5] (Wall 1998; Derpsch 1999). This definition excludes systems in which residues are burnt and crops are planted without tillage (a practice used in ancient times and still used in parts of Mexico, Central America, Asia, and Africa). It also excludes systems in which seed is broadcast on the surface and incorporated with complete tillage (practiced in the Andean Region) and systems in which a small tractor tills the soil and plants the seed in the same operation (practiced in China and other areas of South Asia).

Although the name refers to only one practice, no-till actually is a farm management system that involves many agricultural practices, including planting, residue management, weed and pest control, harvesting, and rotation. The maximum benefits of no-till are obtained only if the package follows the three principles mentioned earlier: that the soil is disturbed as little as possible, that the soil is covered by plants or plant residues, and that crops are rotated. In some places, such as Brazil, packages that do not follow these three principles have been found to be unsustainable; it is not clear yet how sustainability is affected in other locations when one principle is not followed.

Because of technical and economic constraints, packages that combine all three principles are used in only a few locations. The development of sustainable no-till packages requires a strong research effort, especially by interdisciplinary teams, which are difficult to build. Also, short-term economic considerations may prevent farmers from using appropriate rotations. For example, until the mid-1990s, the difference between soybean and maize prices was more than US$ 100/t. Most South American farmers planted a continuous wheat–soybean rotation, even though they knew that the practice increased the risk of infestation by aggressive weeds. The short-term price difference compensated for the expected discounted reductions in yield over the long term.

No-till packages differ by location and type of farmer. The most complex no-till package, such as the one used in South America, is a combination of special machinery (planters, sprayers, and equipment for residue management), agrochemicals (particularly herbicides), and knowledge. Variations of this package have been developed in other locations. For example, the package used in Ghana is basically a weed management system that does not use planters but relies heavily on herbicides. In the irrigated areas of the Indo-Gangetic Plains, where weed management techniques had already been developed for several decades, the development of no-till depended essentially on the design of adequate drills (planters) and water management techniques.

4 In flood irrigated systems, the importance of mulch in no-till is not clear yet. The opinion of most experts is that it should be helpful, but for the time being several technical problems are hindering its use (see p. 4).

5 A cover crop is not planted to be harvested but to protect soil from erosion, help control weeds, and/or eventually increase soil fertility. Commercial crops, in addition to performing some of these functions, are intended for sale. Cover crops are used when no commercial crops are available for a particular growing season. Some cover crops may have an economic value as pastures.

Permanent no-till cannot be used for crops that require massive soil disturbance for their harvest, such as potatoes or groundnuts. However, Brazilian experiences show that planting these crops with no-till can reduce the impact of soil disturbances (M.F. Ribeiro, pers. comm., 2001).

No-till has been adopted mainly in nonarid areas,[6] on soils that are not naturally flooded, or on soils where flood irrigation is not used. In arid areas, where the main objective is water harvesting, the soils are disturbed to meet this objective. In naturally flooded areas, the main objective is to favor drainage and/or evaporation, which are hampered by the mulch used in no-till. In flood-irrigated areas, leveling disturbs the soil, some drills cannot work properly with loose or excessive residue, and the water moves loose residue to the tail of the plot, preventing a uniform mulch cover. These problems are discussed later in the case studies of no-till in the Indo-Gangetic Plains and Mexico.

Among the new technologies being developed for flood-irrigated areas, the use of permanent raised beds is one of the most promising (see p. 22). Raised beds have been used in several countries in rainfed areas to plant row-crops (e.g., maize or soybeans) but not wheat. A reduced-till system called ridge-till has been used in the North Central US since the 1950s. The ridges (or beds) are re-shaped for every crop cycle. Crop residues, if left in the field, are chopped and deposited in the furrows between the ridges. This system is used where wet, cold soils at planting delay field access for conventional tillage and reduce plant emergence. Raised, permanent beds dry out and warm up more quickly, allowing earlier planting and better crop establishment. The furrows also provide drainage for excess water after heavy rains, preventing waterlogging (Sayre and Moreno Ramos 1997).

Researchers working with farmers in irrigated areas of the Yaqui Valley in northwestern Mexico have developed a system in which 2-3 rows of wheat are planted on top of permanent beds, 70-90 cm wide and 15-30 cm high. Wheat is planted on top of the beds, and the furrows between the beds conduct irrigation water. The row orientation of the crop facilitates weeding. Other crops, like soybeans, have also been planted on beds. Irrigation management with furrows is more efficient and requires less labor than flood irrigation. Water savings of up to 50% have been measured with the bed system compared to traditional flood irrigation.

Adapting the technology to local conditions

As mentioned, no-till technology is sensitive to local conditions and requires substantial adaptation from one area to another. Even systems known to work in a given area must be adapted to the conditions on particular farms in that area. For example, the most advanced farmers in South America adapt their practices to individual plots (Ekboir and Parellada 2000). The components that need to be adapted are residue management and crop rotations; planters; control of weeds, diseases, and other pests; and liming and fertilization techniques.

Residue management and crop rotations. Residue management and crop rotations influence soil temperature, moisture conservation, erosion, machinery performance, and weed and pest management. Ideally the soil should be covered with 6-10 t of dry matter per hectare per year, but in drier areas less than 2.5 t have been used successfully. Not only the quantity but the distribution and type of residue are important. Uneven distribution results in poorer performance of planters, herbicides, and the plants themselves: because the amount of residue in any particular spot affects soil moisture and temperature, seeds of the same crop variety will grow differently if residues are distributed unevenly.[7] The type of residue also affects the performance of no-till technology. Some plants, like soybeans, produce too few residues, which also decompose too fast in subtropical environments, making it difficult to maintain adequate soil cover. Other crops, like irrigated rice, produce too much straw, which hinders the performance of drills. Part of this residue must be eliminated, either by accelerating its decomposition, burning it, or removing it from the field.

6 No-till has been used successfully in Australia, however, under as little as 200 mm of annual rainfall, provided that the soil was not degraded (Patrick Wall, personal communication, 2001).

7 Until recently, most combine harvesters would leave too much residue in the center of the header width and too little in the extremes (Derpsch 1999). The latest models have improved straw distribution mechanisms. Strippers for small grains also leave an even cover, since most of the straw is left standing (strippers are harvesters that cut immediately below the spike, leaving most of the plant standing). Additional advantages of this system are the effective control of wind erosion and fewer problems with planters, because the residues are anchored to the ground.

Residue management depends on environmental and social conditions. It is more difficult to produce enough residues in dry environments than in more humid ones. In many developing countries, plant residues are fed to livestock, reducing the amount of residue available for soil cover.

In environments where water availability allows, a permanent cover with a sequence of commercial crops and short-period cover crops results in fewer weeds than in situations where only mulch covers the soil between commercial crops. Derpsch (1999) reports that in some plots there was no need to use herbicides for up to three years. Key to the dissemination of cover crops in South America was the introduction of the knife roller, which enabled cover crops to be managed easily and cheaply. Rotations also reduced weed infestations substantially (Table 1).

Planters. Planter performance depends on local agricultural practices, soil conditions, and residue management practices. In the flat Argentine Pampas, for example, planters are large and heavy in order to cut residues with their weight. The planters usually have a cutting disk in front of the soil opening device; the seed and fertilizer ducts and a compaction mechanism to ensure soil-seed contact (usually a wheel) are behind the opener. This equipment can be used in areas with similar landscapes, such as the Bolivian lowlands or the Great Plains of the US. Even though the landscape in Kazakhstan is also flat and farms are large, Kazakhstan receives half of the rainfall received in the Pampas, so seed needs to be planted deeper to reach the moisture. Planters for Kazakhstan could share many of the characteristics of the Argentine equipment, but the opening devices must penetrate the soil more deeply to place the seed at the right depth. The drills used in southern Brazil have opening devices similar to those used in Argentina but are relatively narrow because they must operate in hilly, uneven terrain. The soil openers of planters used in most countries are mounted independently to adjust to irregular terrain, but the openers on the drills developed for the Indo-Gangetic Plains are mounted on a bar to reduce the price. These drills perform adequately on plots that have been laser-leveled, a technique also required for efficient water management.

Control of weeds, pests, and diseases. No-till creates an environment favorable to beneficial insects and microorganisms, facilitating integrated weed and pest management. Weed control and disease management can be enhanced by combining no-till with other agricultural practices, such as crop rotations and management of irrigation water.

Liming and fertilization techniques. Liming and fertilization techniques for no-till differ from those used in conventional tillage. In no-till, the products are not incorporated into the soil, and the dynamics and interactions of the soil flora and fauna with the mulch are different. For example, the traditional recommendation for acidic soils in the tropics was to apply large quantities of lime every few years and incorporate it into the soil. Recent trials have shown that, since many tropical soils are permeable, small quantities of lime can be applied every year on the soil surface. The lime moves naturally with rainwater into the soil (Derpsch 1999).

Agronomic, economic, and environmental benefits

Compared to conventional tillage, no-till has numerous agronomic advantages (Beck, Miller, and Hagny 1999; Derpsch 1999; Sayre 1998). When combined with residue management, no-till limits soil erosion.[8] It improves water conservation (by increasing infiltration and reducing evaporation) and the condition of the soil (by increasing organic matter content, improving soil structure, and preventing the formation of a plow-pan). Because there is no plow-pan, root systems develop better. The mobilization of nutrients in the soil also improves.

Table 1. Number of weeds per square meter for two soil preparation methods, with and without rotations, Rio Grande do Sul, Brazil

	With rotation		Without rotation	
	No-till	Conventional tillage	No-till	Conventional tillage
Broadleaf weeds in wheat	36	24	102	167
Gramineous weeds in wheat	17	30	41	44
Broadleaf weeds in soybeans	4	20	20	71

Source: Derpsch (1999).

8 Although agronomists do not recommend eliminating contour bounds on slopes of more than 15%, farmers in southern Brazil have eliminated them on slopes of up to 50%. The farmers say they have no erosion problems (Landers 1999).

No-till increases flexibility in the timing of crop operations. The turnaround time between crops is reduced, so crops can be planted closer to the optimal dates. Another advantage is that crops can be planted in soils with higher moisture levels (farmers do not have to wait as long to plant after a rain) or in dry soils before the rains begin.

As described earlier, no-till may also facilitate weed control and reduce pest infestations when used with adequate rotations. Integrated pest management is easier in no-till systems because more beneficial insects are present. In flood-irrigated areas the productivity of water rises as higher yields are obtained with less water. Also, irrigation becomes easier and faster.

The economic advantages of no-till are also numerous. It reduces costs, even for small-scale farmers who buy herbicides, because they replace expensive labor with herbicides;[9] it requires fewer implements as well as less tractor power, reducing investment in agricultural machinery and extending the life of tractors; and it reduces labor requirements and simplifies labor management. Reduced labor requirements enable small-scale farmers to undertake other income-generating activities, such as growing horticultural crops or dairying, provided that they can access the markets. The physical work involved in no-till is less demanding compared to conventional tillage. Larger areas can be planted with the same amount of machinery and labor. In some instances, yields increase with no-till, and in certain areas, three harvests per year become feasible. Production risks fall. Production in marginal areas, impeded by low moisture levels or steep slopes, becomes possible.

In several counties, small-scale farmers themselves have mentioned that with no-till they get a larger and steadier income; the need for family labor falls, allowing children to attend school; they can pay for children's education; and the increased income has enabled families to improve their quality of life.

Finally, no-till has several important environmental benefits. The soil cover reduces erosion and favors water infiltration, diminishing the probability of mudslides in hilly areas and reducing the pollution of waterways with agrochemicals. Pollution may also be reduced as fewer and less toxic agrochemicals are used. Reductions in agrochemicals, combined with the nondisturbance of the soil, favor the development of beneficial insects. Wildlife benefits as shifting cultivation and pollution decrease. Greenhouse gas emissions are greatly reduced by lower consumption of fossil fuels, the smaller amount of organic mater that is transformed into carbon dioxide, and lower methane emissions in nonpuddled rice systems. Increased fertilizer efficiency reduces the formation of nitrous oxides, and due to reduced fertilizer consumption, less energy is used in their production.

Taken together, these benefits give a good indication of how no-till contributes to the agronomic, economic, and ecological sustainability of cropping systems.

Factors encouraging and restricting adoption

Several characteristics of no-till facilitate its adoption when an adequate package is available. First, the economic benefits often become evident in the first year, whereas problems generally do not arise until the third year (see below). Second, the sunk costs associated with no-till are small.[10] The specialized components of no-till are a planter and knowledge. Because no-till planters can also be used for conventional tillage, the only sunk cost would be the small cost of converting a conventional planter into a no-till planter. If a no-till planter replaces a conventional planter, there is a cost only if the conventional planter is replaced before it is completely amortized. The other specialized inputs are the farmer's investments in learning about the technology, which include the farmer's time, the costs of acquiring information (mainly through buying specialized literature and participating in special events), and field trials.

None of these costs is substantial compared with the variable costs invested every year by a commercial farmer, but it is important to note that they can be important for small-scale farmers. As discussed later, large-scale farmers, either individually or collectively, often generate their own information about no-till, whereas

[9] For example, by adopting no-till, small-scale farmers in Ghana reduced their maize production costs by 32% in normal years and 57% every three years, when a new plot had to be cleared under conventional tillage (Ekboir, Boa, and Dankyi 2001).

[10] A sunk cost cannot be recouped if a decision is reversed. For example, as soon as a new car leaves the dealership it loses about 30% of its value. If the new owner finds a buyer just outside the dealership, he has to incur the 30% loss. Sunk costs are usually associated with purchases of specialized equipment and transaction costs.

small-scale farmers often must rely on no-till projects organized and funded by other agents.

A third characteristic of no-till that encourages adoption is that investment indivisibilities are small. The latest generation of no-till planters may be expensive, but many countries have active markets for second-hand equipment. As noted, the technology for converting conventional planters into no-till planters is well known and relatively inexpensive. Even though the transformed planter may not be as effective as a new one, it can do a sufficiently good job.

A fourth advantage is that no-till can be adopted partially or in stages. In many cases, farmers have tried no-till on a small area until they have a good command of the package. Finally, although the technology is complex, the immediate economic consequences of small departures from the optimal package of recommendations are minor. Farmers can learn about the technology over time. If a farmer does not use the best rotation, for example, the consequences are not felt completely in the first year but increase gradually over time.

What are the main restrictions to the adoption and continuous use of no-till? One of the most difficult restrictions to overcome is that no-till requires a complete departure from conventional farming practices. For years farmers have been told about the advantages of reducing the soil to a fine powder. Many researchers, university professors, and government officials also found it difficult to change their professional practices, particularly after they had invested many years in working with conventional tillage.

In switching from conventional tillage to no-till, the farmer must learn about the dynamics of a system that is out of equilibrium and usually takes a long time (more than five years) to reach a steady state.[11] In the first two years of no-till, the farmer obtains benefits from the new technology. The transition to no-till reaches a critical point in the third year, when factors particular to each farm (especially the evolution of pest and weed populations) need to be addressed. Farmers can, and sometimes do, revert to conventional tillage when they face problems with no-till that they cannot solve.

As mentioned, no-till requires substantial adaptation to local conditions. In areas with weak research systems, researchers may develop packages for some regions but not for others. In semiarid environments, it is difficult to produce enough biomass to provide a proper soil cover. No-till may also be difficult to use in areas with sandy soils that have a tendency to compaction, especially in the first two years. In compacted soils, a cultivator or a subsoiler must be used before adopting no-till. In areas covered by snow during the winter, like the Great Plains of the US, mulch delays the thawing of the soil, shortening an already short season. In semiarid and windy areas like Kazakhstan, however, the residues, if left standing, may help to capture snow, increasing the water available for agriculture in the spring.

In many developing countries, residues are used to feed animals. Since plant residues are low quality feed, this demand reflects low-productivity livestock enterprises. To date, farmers have not adopted no-till with mulch in areas where residues are used as feed. It has been suggested that farmers may solve this problem by replacing draft animals with tractors or introducing more productive technologies for livestock (e.g., improved pastures). Because no-till involves a transition from a low biomass producing system to a high biomass system, in some cases the additional biomass may sustain both no-till and livestock. It is possible, however, that farmers will prefer to use the additional biomass to expand their herds.

As mentioned, short-term economic considerations may induce farmers not to use adequate rotations, reducing the system's long-term sustainability. The incidence of weeds, pests, and diseases may increase, especially when rotations are not used.

Plant varieties adapted to no-till agriculture may not be available; often seed companies and national breeding programs develop plant varieties for traditional production systems and more productive cropping environments. Areas considered to have low potential for agriculture under conventional tillage may become high potential areas under no-till, but generally new varieties are not developed for these areas until they have consolidated as major agricultural regions. Very few public research institutions breed plant varieties specifically for no-till conditions (one exception is Brazil's national wheat breeding program, the Empresa Brasileira de Pesquisa Agropecuária–Centro Nacional de Pesquisa de Trigo),

[11] There is even the question of whether a steady state exists and if a system ever reaches it.

although specially adapted varieties may perform better. For example, wheat varieties perform very differently when planted on beds or in the traditional manner, but breeders started to develop wheat varieties for bed planting only recently.

Another potential difficulty in the adoption of raised beds is that they require an initial sunk cost for purchasing specialized equipment and preparing the beds. Unlike no-till planters, bed planters generally cannot be used for conventional tillage. Recently, however, an innovative manufacturer in India produced a bed planter that could also be used as a no-till or conventional drill.

Key Features of Research on No-Till

Before discussing the innovation systems that spurred the development of no-till, it is important to understand some of the ways that research on no-till differs from research on other agricultural technologies. These differences help to explain why innovation networks are fundamental to the development of no-till and why they have evolved differently from networks supporting the development of other kinds of technology. The special features of research on no-till also have implications for formal research programs interested in working on the technology.

Unlike some agricultural technologies, the development of a basic no-till package is not science intensive—even a nonscientist can compare two plots, one cultivated with conventional tillage and the other with no-till. Often farmers and equipment manufacturers can generate their own knowledge with limited interaction with formal research institutions. Researchers themselves can develop no-till packages without necessarily understanding all of the changes occurring in the agricultural system and the environment. Problems that can be addressed only with more formal research approaches (e.g., the evolution of weed populations) arise only after the no-till system is established.

Since research for traditional commercial crops has been conducted for many decades, private firms and public research institutions have a wealth of knowledge that farmers can use. The channels for generating and transferring information about these crops are well established. All of the agents involved in commercial agriculture know where to search for information. These features allow for more distant relationships among the agents involved, usually through markets or printed materials. No-till is a new experience, however. The channels for generating and transferring information as well as the technology itself have to be created, and different agents must collaborate closely (see "Patterns of Innovation," p. 13).

Not everyone can or will collaborate, however. A static organizational perspective, characteristic of many public research institutions in developing countries, has prevented many of them from becoming catalysts or even joining innovation networks devoted to no-till (see "Public Research Institutions and Flexibility for Innovation," p. 9). Despite this limitation, however, some researchers from these institutions have played important roles in the development and adoption of no-till.

The complexity of no-till processes often results in unexpected outcomes that reflect different perspectives among those involved in developing the technology. For example, researchers in Argentina and Brazil found increased soil compaction under no-till and were reluctant to recommend it, but farmers found that increased soil density did not reduce yields or hamper the operation of planters (Ekboir and Parellada 2000a). There is no accepted explanation for why soil compaction had so little effect. The moisture conserved by the mulch and the work of roots and insects may loosen the soil enough to allow planters to penetrate and encourage good crop development (Derpsch 1999). An alternative explanation is that researchers conducted their experiments on small plots where field traffic was intense, whereas farmers produced crops on large plots, which reduced the impact of machinery movements (Ekboir and Parellada 2000). This example highlights two major research issues: the importance of identifying the right indicators to evaluate an experiment (for researchers, it was soil density; for farmers, yields) and choosing the setting of the experiment (the traditional approach is to conduct research on small plots in experiment stations under tightly controlled conditions, whereas no-till was developed through participatory research under commercial conditions in farmers' fields).

Public Research Institutions and Flexibility for Innovation

Most public research and extension institutions in developing countries were created or consolidated in the second half of the twentieth century, when the prevailing policy was to attain self-sufficiency in food production. In this environment, researchers and policy makers were concerned mainly with productivity rather than with competitiveness or sustainability. The focus on productivity provided a stable framework that lasted several decades and prompted public agencies to think in terms of individual crops and not whole agricultural systems. Interdisciplinary work was discouraged by an organizational structure divided by crop and academic discipline (e.g., breeding, soil science, entomology) and by incentives that placed great value on publications in peer-reviewed journals. The financial procedures and the linear vision of science that prevailed among most researchers and research administrators discouraged interactions with extension agents, farmers, and others. Finally, loose quality control of the work of individual researchers gave them no incentive (other than personal motivation) to generate new knowledge or technology. In the mid-1980s, when competitiveness and resource conservation became the most important agricultural policy goals, public research institutions often could not adapt to the new economic and social environment. Their linear vision of scientific innovation (see Figure 1, next page) prevented them from integrating into innovation systems and establishing new incentives more appropriate to the new environment.

Traditional and nontraditional research can contribute to the development of no-till technology in different ways. Traditional agricultural research is a long-term process, in which researchers repeat experiments with a statistical design and few repetitions over a number of years before they issue recommendations. Some of this knowledge can be obtained faster by repeating the same experience simultaneously in many farmers' fields without an experimental design, but other knowledge can be obtained only through formal research in well-equipped and well-funded institutions.[12] Many researchers are reluctant to accept information that was not obtained with traditional statistical methods; sometimes this perspective slows the development of no-till.

Because the environment evolves in response to farming practices, more formal research may be required to ensure that no-till practices remain sustainable. For example, until the late 1990s, the no-till package used most in Argentina was based on the continuous double cropping of wheat and soybeans. Weeds were controlled with glyphosate. After several years, new pests and more aggressive weeds that were not easily controlled with common herbicides were identified, and the development of appropriate weed management practices has become crucial for the sustainability of the system. Other issues also require more formal research: the evolution of soil structure and soil compaction, and the impact of soil structure on crop yields and evolution of soil flora and fauna. Most of this research is science intensive and consequently has to be done by research institutions.

Innovation Systems and Technical Change

Technology generation and adoption have changed substantially in the last quarter of the twentieth century with the emergence of complex technologies.[13] While mass production technologies are basically developed by isolated teams of researchers working in one institution (usually a laboratory within a university or firm), complex technologies are developed by networks of agents that co-evolve with the technologies they generate (Cohen 1995; Rycroft and Kash 1999). The networks usually involve researchers from different institutions along with users of technology, input suppliers, government agencies, non-governmental organizations (NGOs), and financial institutions.

12 The issue here is under which conditions valid scientific information can be obtained from experiments lacking a statistical design. This issue has been largely resolved in sciences that cannot perform experiments and rely on nonexperimental data (e.g., economics, astronomy, ecology). The law of large numbers guarantees valid inferences when enough repetitions are performed.

13 There are many definitions of complexity. In this report it is defined as a system "whose properties are not fully explained by an understanding of its component parts" (Gallacher and Appenzseller 1999).

The key concept for understanding technology generation in this new environment is *innovation*. An innovation is defined as anything new introduced into a productive or social process. This broad definition includes new technologies as well as institutional changes (Archibugi, Howells, and Michie 1999; OECD 1999).

The basis for innovation is learning, i.e., the ability to gather information combined with the ability to use that information creatively in response to market opportunities or other social needs (Lundvall 1999; OECD 1999). Knowledge flows and their transformation into innovations depend on the idiosyncratic characteristics of knowledge, formal and informal regulations (including laws) that regulate interactions among agents, and the history of each innovation network. The agents involved in the innovation process, their actions and interactions, and the formal and informal rules that regulate this system constitute the *national innovation system* (NIS) (Archibugi, Howells, and Michie 1999; Nelson and Rosenberg 1993; OECD 1999).

An innovation does not have to be new for the world or even for the country in which it is adopted, but only for the agent that adopts it. The economic performance of a country or region depends less on the agents that develop the most advanced technologies than on the innovative activities of the majority of agents (in other words, on having many innovative agents) (Nelson and Rosenberg 1993). The dynamics of the NIS depend increasingly on an environment that fosters the emergence of innovation networks, particularly an effective interaction between a country's scientific base and its business community (OECD 1999; Rycroft and Kash 1999).

Two important features of the NIS framework are:

- The evolution of social processes results from the interaction of their history, trends, and random events—that is, processes are path-dependent and unpredictable in the long term. This means that limited predictability is possible, but random events may derail these predictions.
- Processes are not preordained but self-organize through the interaction of many agents. Even though some agents have more clout than others, no single agent has the power to determine the development path.

In the initial stages of path-dependent processes, individuals and small events may have a great influence in defining how the process will evolve—in other words, in "locking" the process into a specific trajectory. After some time, however, the trends become stronger and the ability of individuals to influence the evolution of the process declines (Arthur 1994; Geroski 2000).[14]

Because of the crucial importance of path-dependence and self-organization, this report carefully examines the early stages of the development of no-till packages and the co-evolution of innovation networks and the no-till packages they generate.

The NIS is larger than the national research system (NRS). The NIS can be strong even though the NRS is weak. In these cases, research institutions are weak, but other agents may actively search for new technologies and adapt them to the local environment. Italy is an example of a country with a weak NRS and a strong NIS, which allowed it to develop strong competitive clusters in the textile industry (Malerba 1993). On the other hand, the Soviet Union of the 1970s is an example of a strong research system and a weak NIS.

The traditional analysis of technical change is based on what has been called the *linear vision of science* (Figure 1). In this vision (or framework), knowledge flows start with basic science and continue with strategic and applied research, followed by technology development and ending with adoption. This framework is valid

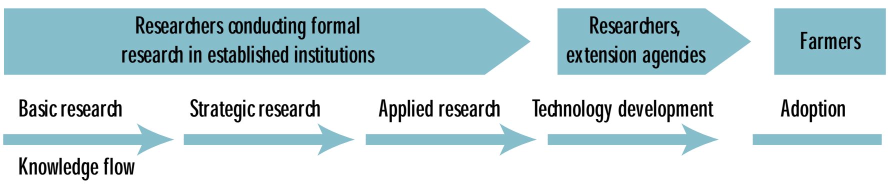

Figure 1. The linear vision of science.

[14] Arthur (1994) studied this feature as an "urn" stochastic process. Assume that you have an urn with two balls, one black and the other white. Draw one ball at random and then put it back in the urn with another ball of the same color. Before the first draw, the probability of extracting a white ball was 0.5. Before the second draw, the probabilities changed to 2/3 and 1/3, a 33% change. Assume that after 1,000 draws, the probability of extracting a white ball is 478/1,000. Before the draw 1,001, the probability of extracting a white ball will be 479/1,000 or 477/1,000, a change of 0.1%. The influence of the first draw on the proportion of balls of each color after 10,000 draws is clearly greater than the influence of the draw 1,001.

only for a limited number of cases; in general, technological developments precede scientific understanding of the underlying phenomena (e.g., the steam engine and thermodynamics) or occur in production lines through the transformation of known processes (as in many Japanese firms) (IDRC 1997; Nelson and Rosenberg 1993).

Unlike the linear vision of science, in the NIS framework (Figure 2) innovations are the result of complex interactions among agents, which include several feedback loops. These interactions can occur at any stage of the processes of knowledge generation and its application to social processes (IDRC 1997; Nelson and Rosenberg 1993). The NIS resembles a spider web more than a linear sequence.

Since agents differ in their innovative activities and abilities, innovation networks arise because no one can pursue all of the steps required to develop and commercialize complex innovations. Agents participate in the network through formal and informal arrangements; additionally, participation in the network changes often, reflecting changes in the agents' objectives and evolving technological challenges.

The performance of innovation networks depends on their *core capabilities*, *internalized complementary assets*, and *organizational learning routines*. Core capabilities are those aspects of innovation in which a particular network excels. Internalized complementary assets are the resources that the network can use to innovate. Organizational learning is the process by which new capabilities and assets are acquired or discarded. The performance of an innovation network also depends on its history, the complementary assets that the network needs to acquire, and the environment in which the network operates (Rycroft and Kash 1999).

Organizational learning is a social process that involves several agents (e.g., producers, input suppliers, output buyers, government agencies, research institutes, researchers, and so forth) interacting in evolving networks. Learning routines within an institution and its ability to exploit acquired competitive advantages depend on internal organizational and governance structures. These routines and institutional structures evolve jointly in processes that are unique to each institution in each country (Cohen 1995; Dosi 1999).

The core assets of no-till networks have included at least a minimal research capability (usually individual researchers from public institutions or agrochemical firms), an institutional culture that valued innovation and networking (especially participatory research approaches), linkages with international sources of information, and at least one institution (with sufficient resources and geographic coverage) willing to play a catalytic role in the emergence of the network. This last factor is crucial. As will be seen, many individual researchers and farmers experimented with no-till in several countries, but widespread adoption occurred only when an institution took the leading role.

The complementary assets of no-till networks have included agents with strong personalities who could organize local networks, a formal research system (not always present), innovative agents (in particular, farmers and equipment manufacturers), and an extension system (either the public system or farmers' associations).

Five new learning routines were introduced by the catalytic agents: participatory research methods, a multidisciplinary approach to research, acceptance of information generated without an experimental design, creation of a common language that enabled communication between agents with different backgrounds, and active gathering and open dissemination of information. These routines required new types of interactions among agents, basically replacing the hierarchical structure arising from the linear vision of science with a horizontal structure in which farmers were partners of researchers and manufacturers.

The dynamics of innovation networks, including the division of labor among public- and private-sector agents, have evolved in the last 30 years because of changes in the organization of the NIS, in the appropriability of innovations, and in the role of the government as an economic agent. Most research institutions in developing countries have had difficulty adjusting to the new environment because they were, and many still are, organized in a way that reflects a linear vision of science. These institutions sought to maximize academic output without regard for future uses; in other words, their objective was to develop research outputs and then display them in the window for someone to take. The consequence was the establishment of weak information flows between

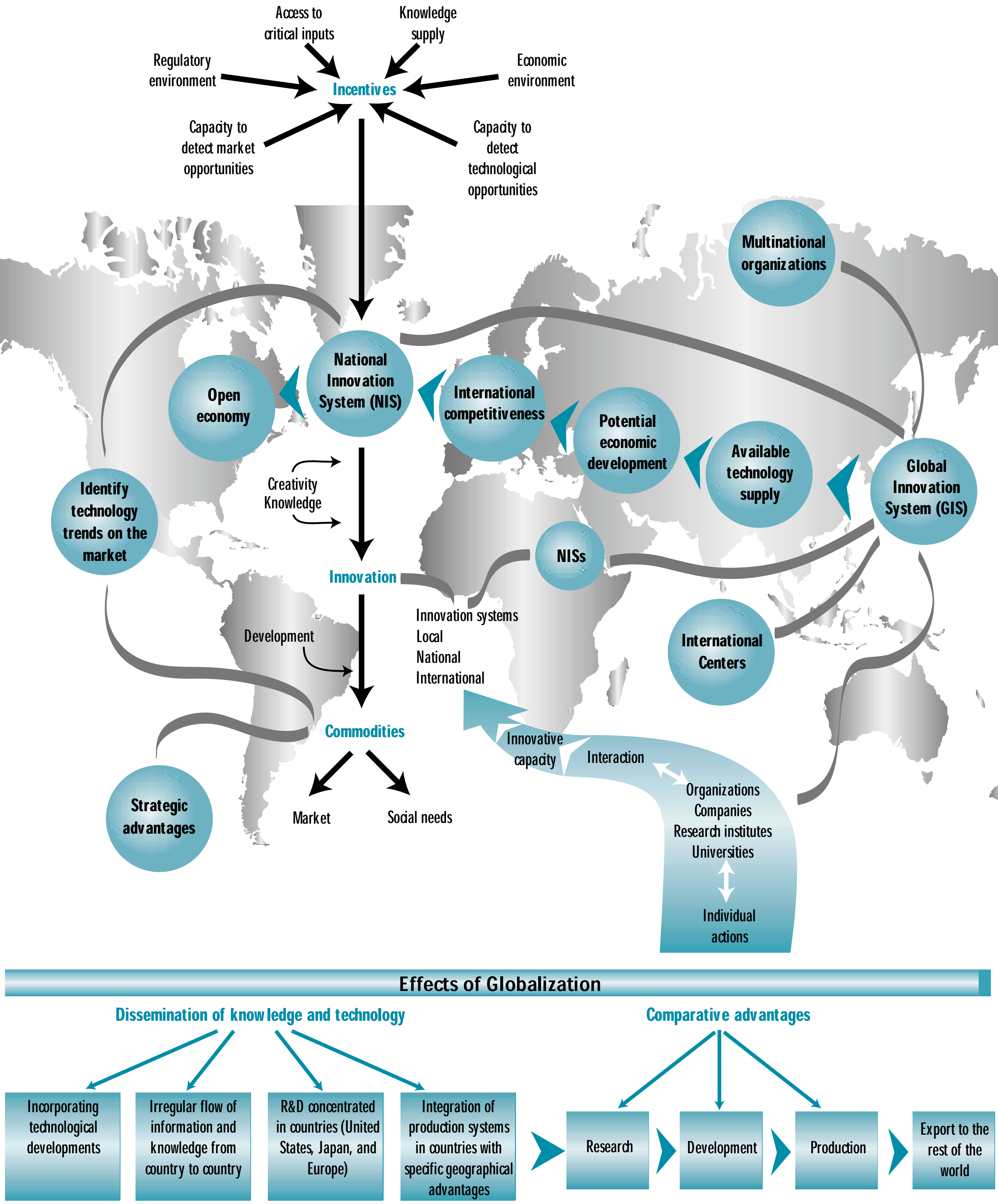

Figure 2. National innovation systems.

Source: Adapted from Ekboir and parellada (2000b).

researchers and users, which resulted in the accumulation of unused technologies and lack of social support for research.

Interactions between researchers and extension agents were also shaped by the linear vision of science, in which extension provided little input to research. Moreover, their interactions were hierarchical: the researcher, being the holder of knowledge, educated the extension agent. This type of relationship was then recreated in the interactions between the extension agent and the farmers.

Within the NIS framework, on the other hand, the emphasis rests on the multiple interactions between researchers, input suppliers, extension agents, and users of the technology. These interactions lead to the establishment of participatory research programs; farmer-to-farmer extension programs with strong support from researchers, extension agents, and input suppliers; and more horizontal flows of information within and between institutions (see "Patterns of Innovation," this page).

Methodological Considerations

This report does not follow the traditional approaches for the analysis of technology dissemination for two reasons. First, no satisfactory indicators of innovation diffusion have been developed because innovation is a broad concept that includes tangible and intangible outputs as well as small organizational changes (Nelson and Rosenberg 1993). Traditional research and development (R&D) indicators

Patterns of Innovation

The evolution of technologies can be classified as fitting three patterns (Rycroft and Kash 1999).

Normal (also known as incremental changes): the co-evolution of an established network and a technology along familiar technological standards. In this pattern there is relatively low technological and economic risk. The interaction mechanisms are known and relatively stable. The innovations are incremental in the sense that they represent minor changes of standard practices. An example of this type of evolution is the replacement of a modern crop variety by another modern variety—a small improvement of an otherwise unchanged agricultural package. The agents who generate the changes do not need to interact closely with the users or other agents because they know the rest of the package and the technological requirements. Most interactions, as well as dissemination of the innovations, are indirect, mediated by markets or printed material.

Transition: the co-evolutionary movement by an established network and technology to a new evolutionary path. The technological risk is greater than in the previous case. The innovation may be introduced into existing production processes, leaving the final product without change. Through these changes, the innovation network remains relatively unaffected but the production process goes through a substantial change. An example of this type of evolution was the introduction of soybeans into Brazilian cropping systems in the 1970s. Agriculture was intensified although most of the agricultural package remained unchanged (see p. 15).

Transformation (also known as revolutionary changes): the launching of a new development path by a new network and a new technology. The technologies represent a major departure from conventional practices and involve major commercial and technological risks. Because the technical standards and market opportunities are not well understood, developers have to interact closely with other members of the network to reduce risk and to obtain all the knowledge required to develop the innovation. Biotechnology is an example of this pattern. The creation and marketing of biotechnology products required the creation of new and more complex networks whose key players included scientists as well as input suppliers, lawyers, government regulators, the media, and non-governmental organizations (NGOs).

Eventually, the transition and transformation patterns evolve into a normal pattern.

As will be seen later, no-till is an unusual example of a transformation pattern. New networks of agents arose to develop knowledge and new products (planters and sprayers) that were integrated into new technological packages that, in turn, were used to produce an unchanged agricultural product (initially grain, but currently vegetable, pasture, and perennial crops).

measure only formal research activities. They do not include resources invested, for example, in design improvement or in enhancing the effectiveness of networks. Second, time-series data on adoption of no-till are incomplete and unreliable, preventing an econometric analysis.

This report also departs from CIMMYT's usual approach in technical research publications in that it emphasizes the roles of individual researchers and unforeseen events. Three reasons justify this approach. First, as explained in the previous section, individuals and chance strongly influence the evolution of a process such as the development of no-till in its early stages. Second, catalytic agents (i.e., institutions and often individuals that play key organizational roles) are an essential component of no-till networks. Third, in their very early stages, new technologies are generally not developed by research institutions but by individuals within those institutions. Only after the technology has shown some potential do institutions organize research programs.[15] Understanding the interactions between the catalytic agents, institutions, and technologies from the early stages of development to maturity is essential to the design of successful no-till programs for small-scale farmers.

Information on the no-till development processes described in this report was gathered through an extensive literature review, complemented by more than 150 semi-structured interviews and field visits in Argentina, Bolivia, Brazil, Ghana, India, Mexico, Pakistan, Paraguay, the UK, and the US. The interviews included early developers and adopters, farmers, researchers, agrochemical companies, and planter manufacturers.

Early Development of No-Till

The next sections of this report consist of six case studies of innovation networks that developed no-till packages for small-scale farmers. These cases highlight the interactions between catalytic agents, institutions, chance events, and history in shaping the networks. This section provides a historical perspective on those case studies by describing the first efforts to develop modern no-till practices, which resulted in packages appropriate for large-scale farmers.

Modern development of no-till started after the discovery of the herbicide paraquat in 1955 and its commercial release in 1961 by the British company ICI. For centuries it had been assumed that tillage was necessary to improve water infiltration and control weeds. Now that weeds could be controlled chemically, ICI funded research to find out if cultivation was still necessary. After the first promising results, ICI realized that a completely new technological package was needed to create a market for paraquat. ICI created in-house research capabilities on agricultural systems by hiring agronomists and mechanical engineers; it also assessed the technical and economic potential of the market for paraquat in several countries. Following these studies, ICI established a research team in Australia in the late 1960s and in Brazil in 1972.[16] ICI's involvement in the US was limited because it had licensed paraquat to Chevron Chemicals and could not develop a market for itself.

In 1960, researchers in Virginia, USA, used paraquat to control bluegrass sod, atrazine for residual control, and 2,4-D for post-planting cleanup. The experiments were soon repeated in other states. The University of Kentucky created a strong research program on no-till, led by S. Phillips. The first use of no-till in commercial production was reported in Kentucky in 1962. The first commercial no-till planter was produced in 1966. To take advantage of the fact that no-till enabled farmers to plant immediately after harvest, the double cropping of wheat and soybeans was introduced in 1966 (Ekboir and Parellada 2000a).

Research on no-till at Massey University in New Zealand started in 1967 (Ritchie, Baker, and Hamilton-Manns 2001) . This program would later be important in the development of no-till in the Indo-Gangetic Plains (p. 23).

Two small groups of researchers from the National Institute for Agricultural Technology (Instituto Nacional de Tecnología Agropecuaria, INTA) and a group of large-scale farmers started research on no-till in Argentina in the early 1970s. Initially each team worked separately but followed the others' advances. Adoption of no-till

[15] For example, despite of two of its centers being pioneers in the development of no-till, EMBRAPA's central office recognized no-till as a major agricultural technology only in the late 1990s, when the area under no-till in Brazil was about 9 million hectares.

[16] The development of no-till in Brazil for small-scale farmers is reviewed in one of the case studies later in this report.

proceeded slowly, because weed control with paraquat was difficult and development of adequate machinery was lagging. In the late 1970s, these groups devised no-till packages based on glyphosate, a herbicide developed by Monsanto. Even though glyphosate greatly simplified weed control, its price made the package economically unfeasible. In the early 1980s, about 15 people (including researchers, extension agents, and farmers) from the three groups started to meet periodically to discuss their progress. In 1987 a Monsanto salesperson convinced this group to create an association of no-till farmers.[17] Monsanto also progressively reduced the price of glyphosate; a liter cost about US$ 40 in the 1970s less than US$ 10 in the early 1990s. By this time, machine manufacturers had developed appropriate planters and sprayers, and with the lower price of glyphosate, the package became technically and economically efficient. The association of no-till farmers was very good at communicating with farmers; in five years, the area under no-till surged from 200,000 to 7 million hectares (Ekboir and Parellada 2000a).

Development of no-till in the US and Australia followed a more traditional pattern than in Argentina, where individual researchers from public-sector institutions were instrumental to developing the technology. In contrast, the US and Australia developed no-till packages mostly through formal research programs in established institutions, with strong participation by farmers and input suppliers. Adoption of no-till grew steadily but relatively slowly compared to South America. In the US, a major restriction on the expansion of no-till was that the mulch delayed thawing of the soil in the spring, shortening an already short cropping season. Also, agricultural policies promoted a range of conservation practices (including minimum till and no-till), which delayed adoption of no-till alone.

The development of an adequate no-till package was technically more difficult in Australia than in South America. Paraquat could not control some of the local weeds (e.g., rye grass). Agricultural practices that combined livestock with crop production caused two problems: unless the pastures were properly managed, the animals increased soil compaction, and it was difficult to control some of the pastures with the available herbicides.

Areas where flood irrigation is used present particular problems that prevent them from benefiting directly from no-till packages developed for rainfed conditions. Considerable research is still needed to develop appropriate no-till packages for flood irrigated conditions; some of this research will be described in the cases presented in this report.

Even though there are no reliable statistics, in 2000/01 no-till was estimated to be used on 59 million hectares around the world, mainly by large-scale, commercial farmers (Table 2).

Table 2. Area (ha) under no-till in different countries, 2000/01

Country	Area
USA	21,120,000
Brazil	13,470,000
Argentina	9,250,000
Canada	4,080,000
Australia	8,640,000
Paraguay	960,000
Bolivia	350,000
Chile	100,000
Venezuela	150,000
Colombia	70,000
Ghana	50,000
Mexico	50,000
Uruguay	50,000
Other	1,000,000
Total	59,290,000

Source: Data for all countries and "other" from Derpsch (2001), except for Ghana (Ekboir, Boa, and Dankyi 2001), India (Peter Hobbs, personal communication 2001), Mexico (from CIMMYT estimates based on fieldwork, and Pakistan (Peter Hobbs, personal communication 2001).

Case 1: The Brazilian Experience

Early research

Starting in the 1960s and for the next three decades, the Brazilian government encouraged an expansion of the agricultural frontier towards the southwest, center-west, and north. Agricultural practices also became more intense as soybeans, as a single crop or in rotation with wheat, replaced livestock and coffee production. These changes, combined with the heavy rains, hilly landscape, and conventional tillage, led to serious soil erosion, and public research and extension institutions recommended that farmers switch to livestock production. Some farmers, wishing to avoid the economic losses involved in moving to livestock production, began experimenting with reduced tillage.

In the late 1960s, the German cooperation agency GTZ (Deutsche Gesellschaft für Technische Zusammenarbeit) hired Rolf Derpsch to work on a newly established

[17] Monsanto paid for all startup costs and for operational costs in the first year.

research project in Londrina, Paraná to increase soybean yields; the project was based in IPEAME.[18] Derpsch began testing alternative practices, including an early version of no-till. Encouraged by the results, he teamed up with Herbet Bartz, a farmer who was willing to test the technology on his farm.

When ICI transferred its no-till research team from Australia to Londrina in 1972, the team established strong relationships with the agents working on no-till: Derpsch; a few researchers, mainly from IAPAR, the Agronomy Institute of Paraná (O Instituto Agronômico do Paraná), and the Wheat Center of the Brazilian Agricultural Research Corporation (Empresa Brasileira de Pesquisa Agropecuária–Centro Nacional de Pesquisa de Trigo, EMBRAPA-CNPT); a planter factory (Semeato);[19] and pioneer farmers. ICI became the hub of a system that developed the first no-till package for Brazil. The keys to its success were its strong development team, its participatory and multidisciplinary research strategy, and a strong sales force that promoted no-till. The new learning routines induced major changes in formal research methods by fostering collaboration among researchers, equipment manufacturers, and farmers.

In 1972, Bartz traveled to the UK and the US with the help of ICI to learn more about no-till. Back in Brazil the next year, forced by the loss of his crop to sell all his machinery except a no-till planter acquired overseas (it had only scrap value), Bartz had to plant his farm with no-till—the first large-scale use of the technology in South America. Technical difficulties and the lack of a network delayed the spread of no-till, however. The no-till package was still in its infancy, especially the machinery and weed control practices.[20] The planters that were available were inadequate for Londrina's heavy soils. Bartz continued to collaborate with Derpsch and ICI but, as he was uninterested in promoting no-till, a network to disseminate the package did not emerge.

In 1974, ICI imported a no-till planter and lent it to research teams, equipment factories, and farmers. Small workshops started to adapt the planter to local conditions with support from EMBRAPA-CNPT and ICI. ICI mobilized a large sales force to promote no-till among pioneer farmers. Formal research was concentrated in two institutions, IAPAR and EMBRAPA-CNPT. All other research and extension institutionss, including the universities, opposed the technology until adoption was widespread.

The severe erosion problems forced many farmers to default on their loans. In the early 1970s the manager of the Castro (Paraná) branch of the Banco do Brasil[21] convened a meeting of researchers and extension agents to find a technical solution to this problem. Following the guidelines of the US Soil Conservation Service, they recommended the construction of terraces and prepared a chart that related the distance between terraces to the slope of the terrain. When farmer Manoel Pereira's loan request was rejected in 1976 because, according to the chart, his land was regarded as too steep for terracing,[22] he sought the advice of an agronomist who thought that no-till might increase the distance between terraces and enable the use of machinery. The first no-till trial succeeded. A few neighbors also tried no-till with help from ICI. After three years, these farmers felt they needed to seek specialized advice abroad. Pereira and Franke Dijkstra visited the University of Kentucky's no-till program. Pereira and Dijkstra had very strong community ties and were very active in their farming cooperatives. Upon their return, they encouraged the creation of the Earthworm Club to exchange no-till experiences. Many members of their cooperative were small-scale farmers. Pereira and Dijkstra were instrumental in convincing three neighboring cooperatives to organize an extension program for them. Eventually, the Earthworm Club and this program evolved into the ABC Foundation,[23] a research and extension institution funded by the three cooperatives. An active collaboration between the cooperatives and University of Kentucky emerged from the visit to the US. Professors and graduate students

[18] This center would later become EMBRAPA's Soybean Research Center.

[19] ICI contacted several manufacturers of agricultural machinery, but most were not interested in a new technology for which they did not see a market. The owner of Semeato, a small factory at that time, was also a farmer interested in conservation tillage. He immediately agreed to participate in the development of planters for Brazil. Eventually Semeato became the largest manufacturer of no-till planters outside the US.

[20] In certain years Bartz manually weeded over 600 ha of soybeans.

[21] The Banco do Brasil was then the most important lender to the agricultural sector.

[22] According to the chart, the terraces should be one meter apart.

[23] In 1998 the ABC Foundation had a budget of about US$ 1 million.

from Kentucky often visited Brazil, and many of the cooperative's professionals received training in the US.

The introduction of glyphosate and continuous research by several agents (public-sector researchers, farmers' organizations, agrochemical companies, and machinery factories) produced an efficient no-till package by the end of the 1970s. The main hurdle to adoption was the high price of glyphosate. At this time, the governor of Paraná barred IAPAR from researching no-till on the grounds that it was a technology for large-scale farmers, promoted by a multinational company. IAPAR was to concentrate on technologies suitable for small-scale farmers. Though these directives were eventually reversed, IAPAR never regained its relevance as a major player in the development of no-till.

After the success of the Earthworm Club, small groups called Clubes Amigos da Terra (Friends of the Land Clubs) were created in the southern states with support from farmers and agrochemical companies. These small groups were a successful innovation. Periodic meetings and stable membership fostered trust and allowed farmers to discuss their technical problems openly.

Because weed control was easier with glyphosate than paraquat, Monsanto eventually captured most of the herbicide market for no-till. Despite ICI's huge investment in creating a market for paraquat, a first-class research team, and an innovation network, no-till was a commercial failure, and ICI cut all no-till activities in the late 1980s.

During these years, Derpsch interacted actively with agrochemical companies, individual farmers, and farmers' associations. He organized a research program on cover crops as well as no-till associations.

No-till for smallholders

Until the 1990s, small-scale farmers' adoption of no-till was limited. They could use the same crop rotations, herbicides, and cover crops as large-scale farmers but lacked technology for planting by hand or with animals. Three major projects (METAS, Paraná Rural, and Land Management Project II) in the 1990s fostered adoption of no-till by small-scale farmers by developing adequate planters and training extension agents.

The METAS project involved several public- and private-sector agents. In 1990, a researcher from EMBRAPA-CNPT and a Monsanto technician investigated the causes of limited adoption of no-till by small-scale farmers in Rio Grande do Sul. They identified three factors: the need to adapt the package to local conditions, lack of adequate planters for small-scale farmers, and insufficient command of the package by extension agents. Following this diagnosis, in 1993 Monsanto promoted a project that supported research as well as extension. The project involved five public and private institutions, selected to cover the spectrum of problems to be solved. In the first year of the project, the area under no-till jumped from 45,000 ha to 150,000 ha. By 1997, the area under no-till had reached 820,000 ha in the project area (90% of the target) and 2,200,000 ha in the whole state. This success induced other agents to join the program; in the third year, partners included seven private companies, three public research and teaching institutions, the extension service, local planning offices, cooperatives, and municipal authorities. The project had a budget of about US$ 400,000 for the first three years.

The project's most relevant activities were the adjustment of cover crop management practices to regional circumstances, the validation of low-cost kits to enable small-scale farmers to convert conventional planters to no-till planters, the adjustment of recommendations for liming and fertilizer management, the improvement of chemical spraying technology, the training of extension agents, the implementation of Training Demonstration Units in farmers' fields, and the establishment of a research Demonstration Farm (Denardin and Kochhann 1999). Public- and private-sector partners in METAS shared human, material, and financial resources to coordinate activities and reduce risk. The EMBRAPA centers and the Universidade Federal de Pelotas were responsible for conducting research and training extension agents. The state extension service and private extension agents worked with cooperatives to install Training Demonstration Units. These units served first as a means of self-training for extension agents and later became demonstration plots for farmers and local communities. Additionally, the extension agents provided feedback to the research teams. The private companies financed part of the costs, contributed with their own research, and interacted with researchers and extension agents.

Before the METAS project, planters were relatively large and expensive (above US$ 10,000). Many of the repair shops that improved the low-cost kits for adapting conventional tillage equipment to no-till became manufacturers of cheaper seeders, offering prices as low as US$ 7,000. Semeato was induced to reduce the size of its equipment and lower its prices to meet small-scale farmers' requirements.

In Londrina, technical problems with no-till had been solved by the late 1980s, but adoption was still confined to large-scale farmers. In 1988 a group of state technicians formulated the project Paraná Rural. With financial support from the World Bank, the project (implemented between 1989 and 1996) eventually involved 210,000 farmers on 7.1 million hectares. By combining micro-catchment planning with planning on individual farms, the project marked the evolution from a purely physical approach to soil conservation (use of barriers) to an integrated soil management approach in which no-till was the key component (Landers 1999). The Project Coordinating Unit and the Regional and Municipal Soil Commissions used decentralized, participatory approaches for implementation. The project supported farmers' associations and group purchases of equipment. Training programs for implementing institutions and officials ensured that consistent information was given to farmers. Soil conservation legislation enacted by the state government was an important tool for extension agents to convince the most reluctant farmers to adopt soil conservation technologies. The project also included credit lines for the poorest farmers. A parallel project was implemented by IAPAR, the extension service, the state government, and the Brazilian Association of No-till Farmers. In this project, 31 planters for small-scale farmers were bought by the state and placed in 31 communities for the farmers to experiment with the technology. Extension agents and farmers were trained in the use of no-till.

In the state of Santa Caterina, the Land Management Project II also used the micro-catchment as the planning unit. In 1984 three pilot projects were set up to develop soil conservation and other sustainable practices, building on previous research and farmer experiences with cover crops. That same year, watershed commissions in the project areas were created. The first experiences of no-till with animal-drawn planters occurred in 1987. The machinery and the rest of the no-till package were improved in the following years. Massive adoption by farmers started after 1991; by 1999 it was estimated that over 80% of the state's grain area was planted with no-till (Landers 1999). Technical support for this project was provided by EPAGRI, the state research and extension enterprise. The project was followed in 1998 by the Pro-Palha Project, a partnership between seven agribusiness firms, EPAGRI, and two cooperatives.

Case 2: The Bolivian Experience

Crop production in Bolivia is concentrated in two environments: the eastern lowlands (150-700 masl) and the Andean Valleys (1,000-3,600 masl). Most small-scale farmers are found in the Andean Valleys. In 2000, an estimated 350,000 ha in the lowlands were planted with no-till. Adoption of no-till in the valleys remains minimal, since a basic package is still being developed.

No-till in the lowlands

The lowlands were opened to agriculture in the 1980s. Large-scale and mid-size farmers predominate, generally growing summer soybeans with wheat, sunflower, or sorghum sown in the winter in a double crop system. Rainfall averages 1,300 mm and is concentrated in the summer months; wheat is planted in May into residual moisture after the summer soybean crop is harvested.

A few farmers developed no-till practices in the 1980s without support from formal research institutions. In 1993, the Association of Oilseed Producers (Asociación Nacional de Productores de Oleaginosas, ANAPO) asked CIMMYT to post an agronomist to eastern Bolivia at Santa Cruz de la Sierra to improve wheat technologies and the profitability of the soybean-wheat rotation (no-till was not considered as a specific instrument.) Patrick Wall, a CIMMYT wheat agronomist, was posted from Paraguay to Bolivia in 1994 and started to promote no-till.

No-till, combined with crop rotation, has a strong positive impact on wheat production. Wheat yields increase about 25 kg/ha for each additional millimeter of moisture in the soil. In the lowlands, in a dry year like 1998, plots seeded with conventional or vertical tillage yielded 450 kg/ha of wheat. Plots seeded with no-till without crop rotations yielded about 600 kg/ha. When no-till was combined with rotations, yields of 900 kg/ha were obtained (Patrick Wall, personal communication, 2001).

Small-scale farmers did not adopt no-till because suitable planters were not available; on areas under 150 ha, mechanized no-till was less profitable than traditional practices (Paz 1998). Large-scale farmers adopted the technology to save on production costs—especially diesel—and because they could extend the planting period from about 3 days after the first rains to about 12 days. The short seeding period prevented the emergence of a market for custom services to serve smallholders.

Over the years, two specialized no-till networks emerged; they worked separately but followed each other's progress. CIMMYT organized a network with public research institutions, farmers' associations, and progressive farmers to deal with agronomic issues in wheat production and develop appropriate machinery for small-scale farmers. A second network, formed by Fundacruz,[24] agrochemical companies, and farmers, specialized in weed management. Carlito Los, an agronomist with the ABC Foundation (Brazil) who was hired by the main Bolivian agrochemical distributor, was critical to the development of a weed-management package. The agrochemical company provided new information and conducted some research with farmers.

Public research was severely challenged in 1998, when the Bolivian Institute of Agricultural Technology (Instituto Boliviano de Technología Agropecuaria, IBTA) was closed and the Center for Tropical Agricultural Research (Centro de Investigación Agrícola Tropical, CIAT), a state research center in Santa Cruz de la Sierra, lost most of its funding. To sustain wheat research, the National Wheat Program (PROTRIGO), incorporating CIAT and ex-IBTA researchers, ANAPO, three NGOs, and CIMMYT, under the Ministry of Agriculture, was initiated with funding from the US and the European Community. This program financed much no-till research and promotion between 1998 and 2001. Formal agricultural research in the lowlands is now conducted by CIAT and CIMMYT working with ANAPO. CIAT soil scientists have been more active in promoting vertical tillage researched with a previous British technical aid mission, whereas CIAT wheat agronomists, CIMMYT, and ANAPO favor no-till.

Drawing on experience gained in Paraguay (see p. 31), Wall established large demonstration plots in farmers' fields with farmer collaboration; these experiments had a fairly sophisticated design to derive statistically valid inferences. Second, farmer groups, field days, bulletins, and events were established. Third, public-sector researchers were encouraged to work on no-till.

Unlike other South American countries, in Bolivia the medium- and small-scale farmers in the lowlands have been more interested than large-scale farmers in collaborating with researchers.[25] Small-scale farmers usually own 50 ha, of which 15-20 are sown to grain crops. Owing to past subsidies, most small-scale farmers are mechanized. Efforts to develop a no-till package assumed that small-scale farmers were eager to use their tractors, but when Wall invited Magin Meza[26] and Marcos Peñalva to give talks to small farmers in the lowlands, they showed pictures of animal-pulled planters that interested small-scale farmers because they would need no bank credit to use the equipment. Soon, in collaboration with ANAPO, Wall held a series of field days on animal-drawn equipment (Brazilian and locally made).

No-till in the highlands

In the Andean Valleys, where farmers usually own 1-5 ha, farm sizes have been falling with successive generations. Most farmers combine livestock with crop production. During the winter, the animals are heavily

24 Fundacruz is a farmer-funded research foundation that follows the model of the Brazilian ABC Foundation.

25 Owners of large-scale farms are usually business people with little involvement in agriculture. Managers of these farms are interested in collaborating but have limited decision-making power about the use farm resources.

26 Magin Meza is a Paraguayan extension agent with vast experience in developing no-till packages for small-scale farmers.

dependent on crop residues (Wall et al. 2000). Rainfall in the valleys varies between 300 and 700 mm/yr and is concentrated in the summer months (November-April).

In the more fertile regions or in areas where summer rainfall exceeds 500 mm, farmers grow wheat, maize, potatoes, broad beans (*Vicia faba*), and peas (often harvested as dried peas) in different rotations. In the less fertile or drier regions (less than 500 mm rainfall), wheat or barley monoculture, broken by occasional weedy fallows, is common. After each crop, plots were left fallow for two years, but this practice is being abandoned as farm sizes decline. Most crops are hand harvested, and the small grain cereals are threshed away from the fields. After the threshing, the straw is stored for animal feed.

In 1994 IBTA and CIMMYT surveyed farmers in the Andean Valleys and found that the two main constraints to wheat production were drought stress and soil erosion (mainly hydric). These two problems had received little attention because researchers assumed that drought stress could not be solved by technical means. To demonstrate that cover crops could have an impact on soil moisture management, Wall imported a few Brazilian no-till planters.

Until its closure, IBTA was CIMMYT's most important research partner. After 1998, PROTRIGO funded and coordinated most research and extension activities; the latter were contracted to NGOs and farmers' associations. The only other major research partner is the Universidad Mayor de San Simón in Cochabamba, although an FAO project which terminated two years ago did establish some no-till work using Brazilian drills. FAO has also conducted a training course in the Tarija Department.

The Universidad Mayor, together with PROTRIGO and CIMMYT, has developed an animal-pulled, no-till drill for small grains in collaboration with the Silsoe Research Institute (SRI) (a British research institute) and several NGOs that support the diffusion of the technology. The development of the drill was partly funded by project managed by SRI and funded by the UK Department for International Development, in which the Universidad Mayor manufactures the drills and the project purchases them at a cost of about US$ 330 per unit. Another development by the CIMMYT project was the manufacture of a human- or animal-drawn sprayer, based on a Brazilian model. Several machines, based on this initial model, are now being produced by the Universidad. Before this local drill was developed, small-scale farmers had to rely on Brazilian equipment, which was too large. As noted, they could not resort to custom planting for wheat because of the short planting season.

Until 2001, few farmers participated in researchers' on-farm trials. With the purchase of 10 drills in 2001, small-scale farmers, NGOs, and a municipal government became more actively involved through courses on no-till and printed materials. Farmer adoption remains minimal owing to the lack of machinery and of sufficient residues for no-till as well as livestock. Soil cover is difficult to maintain because fields are open for communal grazing in late June and, as wheat is harvested by hand and threshed away from the field, farmers do not want to incur the expense and trouble of returning the straw to the field. The communal grazing problem could be solved by controlling the sheep, making the residues unpalatable, or introducing pastures in fallowed plots. Given that no-till increases the amount of residues produced, adopters could potentially have enough residues to maintain their herds and a proper soil cover.

The introduction of combines could also increase the feasibility of no-till. Recently, one NGO started offering custom harvesting with a combine, and farmers immediately realized the savings of money, time, and effort that could be achieved.[27] Since demand for the combine is large, the NGO gives priority to the best fields, providing an incentive for farmers to adopt a more intensive production package. One byproduct of mechanical harvesting is that the straw remains on the soil. Even if it is later grazed by sheep, enough straw remains to provide cover.

[28] With combine harvesting, farmers can remove wheat from the field in a few hours compared with the three months usually required by manual harvesting, threshing, and winnowing. In addition, the mechanically harvested wheat has higher quality because it is not mixed with stones and manure.

Case 3: The Mexican Experience

Mexico's research and extension institutions have been organized along scientific disciplines or crops, reflecting the linear vision of science discussed earlier. Their structure has tended to be relatively rigid and hierarchical. Collaboration among scientists, even from the same institution, has been infrequent, researchers have had little say in the programs designed by their directors (Ekboir et al., forthcoming), and they have worked in small plots on experiment stations, seldom interacting with extension agents and farmers. "Finished technologies" were passed to extension agents who would then transfer them to the farmers, usually as part of a program that included subsidies. The technologies to be promoted were selected by the public officials in the capital city who designed the programs in a top-down manner with little participation of farmers or local governments (Kondo 1999, van Nieuwkoop et al. 1992). Farmers began to expect monetary incentives to be attached to extension programs.

Trials on no-till without mulch were conducted in the 1950s by the predecessor organizations of the Instituto de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP), Mexico's national agricultural research organization, but this line of research was soon abandoned due to disappointing results (Claveran 2000).

When the success of the Green Revolution in South Asia[28] led the Mexican government to promote a similar package in the 1970s, the resulting intensification of agriculture created erosion problems in the hilly Mexican landscape, and research on conservation practices was initiated. In 1973, CIMMYT started its own research and training program on no-till for maize. CIMMYT researchers, trainees, and visiting scientists (including trainees and scientists from Mexico) conducted research on experiment stations and in farmers' fields around the world (Soza, Violic, and Haag 1998). In the late 1970s, CIMMYT organized a study tour to the US by technicians and researchers from Fideicomisos Institutidos en Relación con la Agricultura (FIRA)[29] and INIFAP's predecessor organization to see conservation agriculture. Upon their return, these institutions started no-till programs in their respective domains: INIFAP in research and FIRA in promotion (Claveran 2000).

FIRA initiated a no-till program that trained farmers, built specialized training centers, established a large network of demonstration plots, promoted conferences and farmers' organizations, and, foremost, financed equipment purchases (González 1990). INIFAP conducted a few isolated trials in the 1970s and 1980s. Research accelerated at the beginning of the 1990s, and in 1996 INIFAP created CENAPROS, a center devoted to sustainable agriculture which coordinates all institutional activities related to no-till. In the late 1990s, 55 researchers participated in INIFAP's national program on conservation tillage (Claveran 2000). From the 1980s, the Colegio de Postgraduados (CP), a graduate teaching institution, also supported research and extension related to no-till. Most of the research was done for masters' and doctoral theses, in particular on soil topics. The CP's relationship with farmers has been top-down and the research has had little impact in the field.

This specialization of tasks reflects the lack of interaction between the three institutions: since no package had been developed for the different Mexican environments and with little support from INIFAP or the CP, FIRA had to do its own research. At the same time, neither INIFAP nor the CP had extension programs. Despite their similar programs and several institutional agreements to develop joint projects, interaction between researchers from these institutions remains limited.

Others involved in no-till in Mexico have included NGOs, private companies, and farmers themselves. A network partially financed by the Rockefeller Foundation includes universities, research institutions, state governments, and other NGOs (Claveran 2000). A few private companies organized no-till extension programs that failed because their traditional structure discouraged efforts to develop an innovation network and a package adapted to local conditions. For example, John Deere promoted groups of no-till farmers, but its main goal was to sell machinery imported from the US.

28 The Green Revolution package included high-yielding, input-responsive wheat and rice varieties, improvements in irrigation, and increased fertilizer use. The Indian government promoted this package aggressively with important subsidies for inputs and outputs.

29 FIRA is a set of trust funds administered by the Banco de México with a budget of about US$ 2 billion. FIRA combines extension and financing of agriculture. No-till is one of several programs.

Similarly, although Monsanto promoted no-till, it did not support development of a package. Technical difficulties have now led Monsanto to emphasize minimum tillage (seen as a precursor to no-till).

Farmers have also been exploring no-till options. In certain areas of the southern state of Chiapas, for example, farmers used to plant in communal plots in a system that included long fallows. These very steep areas cannot be planted with conventional techniques. After titling of the land in the early 1990s induced an intensification of agriculture and abandonment of the fallow, farmers developed a no-till system based on the use of herbicides and manual planting (Mauricio Bellon, personal communication, 2001). The origin of the package is not known, as no institution has claimed credit for its development.

Prototype planters for small-scale farmers have been developed by INIFAP and the Universidad Autónoma de Chapingo, but they have not been tested by farmers nor reached commercial production. A few Mexican manufacturers and two multinational companies (John Deere and New Holland) produce no-till planters and drills for small-scale farmers (Claveran, 2000). Demand for this equipment is small because of design problems and because the rest of the package has not been developed.

In the 1990s, CIMMYT and the Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), the French cooperation agency, had a joint no-till program in the state of Jalisco. Though valuable agronomic information was produced, the program (organized as traditional on-station and on-farm research) had little impact on Mexican agriculture. In 1999 it was reorganized to incorporate participatory methodologies and relocated to the Bajío area in central Mexico; it is too soon to evaluate this new stage.

Declining water tables and falling prices are forcing farmers in Mexico's irrigated areas to seek alternatives. Partial adoption of no-till, such as its use for only one crop in a two-cycle annual pattern or no-till without soil cover, has been documented in several areas (Erenstein and Cadena 1997). Recent fieldwork in the Bajío indicated that farmers are aware of conservation tillage technologies. More than 60% of large-scale farmers had heard about the technology compared to 36% of small-scale farmers. All farmers, however, had insufficient knowledge of the package (Erenstein 1999). Adoption in the rainfed areas has been negligible, but in irrigated areas more than half of the farmers use conservation tillage in the spring crop, followed by heavy tillage for the winter crop. Obstacles to the full adoption of no-till in the Bajío are: 1) plant residues have a market as animal feed, 2) it is difficult for individual farmers to keep their land covered, given the common practices of burning residues and communal grazing, 3) residue management practices are not available, and 4) neither are adequate planters. Along with its research on no-till for maize, CIMMYT worked with farmers to develop new planting techniques for wheat in irrigated areas of the Yaqui Valley in northwestern Mexico (Sayre and Moreno Ramos 1997).[30] Trials initiated in 1961 by R.J. Laird, a soil scientist and agronomist, showed that wheat yields were not affected over a large range of spacings (from 17 to 70 cm), indicating that it was feasible to modify planting patterns. In 1968, O.H. Moreno Ramos joined the research team in the Yaqui Valley. Over the next decade, he conducted a series of experiments that laid the basis of the bed planting system, particularly planting on beds rather than flat land and using furrow rather than flood irrigation. A concerted effort was made to familiarize Yaqui Valley farmers with this technology. In 1981 only 6% of farmers were planting on beds; at present over 90% use the system. Bed planting reduces costs, reduces water use, and permits farmers to combine a pre-seeding irrigation with mechanical cultivation as a weed control strategy, reducing herbicide use (Sayre and Moreno Ramos 1997). The advantages identified by farmers include higher yields, reduced costs, easier weed control, and reduced turnaround time between wheat and a summer crop.

Most farmers practicing bed planting burned the crop residues, tilled the soil (destroying the beds), and formed new beds to sow wheat after the summer crops. In the early 1990s, Kenneth Sayre, a CIMMYT wheat agronomist, started working with farmers to develop permanent beds, which would eliminate the cost of forming beds every year and yield the benefits of no-till. Production costs fall as plowing is

[30] The Yaqui Valley, in the northern state of Sonora, was the center of the wheat breeding program initiated by Norman Borlaug and colleagues under a Government of Mexico-Rockefeller Foundation collaboration in the mid-1940s.

reduced. Permanent beds also reduce the loss of sediment in the irrigation tail because these beds are more stable than beds established after conventional tillage prior to irrigation. Crop residues in the furrows help stabilize the soil and reduce soil erosion by water (Sayre and Moreno Ramos 1997). The controlled traffic of field equipment (the wheels pass only over the furrows) reduces soil compaction.[31] The technology is still in the early stages, however, especially the development of no-till bed planters that can plant through residues and of wheat varieties adapted to bed planting.[32]

There is no agreement on the level of adoption of no-till in Mexico. FIRA recently estimated the area under no-till at about 650,000 ha (Ochoa 1999), based on the number of no-till drills delivered through several promotional programs. Recent CIMMYT fieldwork shows that those programs emphasized "hardware" over "software": the machines were delivered but farmers were not trained to regulate them or to manage residues. Consequently, most farmers use the no-till drill for conventional tillage.

The apparently low adoption of no-till in Mexico reflects the inability of all agents working on the topic to integrate into an innovation network. Development efforts remained isolated. Until recently, there was no attempt (except in the Yaqui Valley) to involve users and local equipment manufacturers. A catalytic agent for a network failed to emerge, largely owing to the top-down organization of research and extension and the linear vision of science that hampered inter-institutional collaboration. These shortcomings affected not only public institutions but also CIMMYT and private firms. Bed planting, on the other hand, was developed because of the early emergence and persistence of a strong localized research program, the strong innovative attitude of farmers, their need to cut costs, and their close collaboration with CIMMYT and research institutions in the 1990s.

Case 4: The Indo-Gangetic Plains Experience

Because of its many environments and rainfall patterns, the Indo-Gangetic Plains region in South Asia (Map 1) presents a formidable challenge for the development of permanent no-till packages—i.e., mutually compatible no-till technologies for the most common crops, especially the rice-wheat sequence. Soil and hydrological situations differ throughout the Indo-Gangetic Plains. Rainfall is more limited in the west, where the most productive areas are irrigated, whereas the lowlands of the eastern Indo-Gangetic Plains are naturally flooded for periods of variable duration. Rice is planted in the wet, warm season and wheat in the dry, cool season. Rice grows in areas receiving as little as 120 mm of rain and in areas with more than 1,800 mm, and under full irrigation or only as a rainfed crop. Wheat is grown under similar circumstances, although most wheat fields receive at least one initial irrigation. Traditionally, rice is planted in damp soils after thorough plowing, which negatively affects soil properties (see "Problems in Rice-Wheat Systems," p. 24). Wheat is then planted in these degraded soils. The rice-wheat system dominates the irrigated areas, whereas a larger variety of cropping patterns are found in the rainfed areas in response to different environmental conditions (Kataki, Hobbs, and Adhikary 2001).

No-till wheat in the Indo-Gangetic Plains

Only one basic no-till package for wheat is available for the region. Though substantial efforts are being made to develop new planting techniques for rice, these are still in their infancy (see "No-Till for Rice," p. 25). Research on no-till for other crops is conducted only by isolated researchers and innovative farmers. Efforts to develop no-till packages for rainfed conditions have been weak.

Map 1. Indo-Gangetic Plains (dark area on map).

[31] In another major irrigated area (El Bajío, in central Mexico) farmers successfully experimented with wide beds of 2-3 m (Bernard Triomphe, personal communication, 2001).
[32] Preliminary trials show strong variability in the response of wheat varieties to bed planting.

Problems in Rice-Wheat Systems

A number of problems affect rice-wheat systems in the Indo-Gangetic Plains of South Asia. Support prices for rice and wheat and input subsidies (for agrochemicals, electricity, and water) make the rice-wheat rotation the most profitable and least risky option for farmers while inducing excessive input use (Pingali and Shah 2001). These policies have hampered the development of markets for other crops; since alternative crops present more market risk than rice or wheat, farmers are less likely to grow them.

Another problem is that the soil is managed in completely different ways for rice and wheat. Traditionally rice is produced by plowing saturated soils (i.e., "puddling") (some dry-seeded, nonpuddled rice is found, however, mainly in rainfed areas). Puddling reduces water loss and controls weeds in rice, but it leads to deterioration of the soil's physical structure, formation of a hard pan at a shallow depth, poor water infiltration, waterlogging, and poor root development. Physically degraded soils create problems for the wheat crop, because farmers have to make many passes with a plow to prepare an acceptable seedbed. Tilling with animal traction is more prevalent in the eastern areas where yields are lower. Commonly, farmers in these areas make six to ten passes with a local plow (a wooden stick with a metal point), followed by the same number of plankings (a heavy wooden log that compacts and breaks clods). Tractor power is rapidly replacing animal power and is the major power source in the higher production areas of the western Plains. Although tractors enable faster and more thorough land preparation, farmers still make six to eight passes with a nine-tine cultivator or disk harrow, usually followed by planking, to prepare the land for wheat (Hobbs and Giri 1998).

Late planting is another problem; yield potential declines by 1-1.5% per day when planting occurs after 20 November. The three major causes of late wheat planting are delays in planting rice due to drought, late harvest of the previous rice crop, or long turnaround time from rice harvest to wheat planting. Late harvest results from the use of long-duration rice varieties,* late rice planting, or the production of a short-duration crop after rice. The long turnaround time is caused by excessive tillage, soil moisture problems (too much or too little moisture), power constraints for plowing, or by the need to thresh and handle the rice before plowing the soil for wheat (Hobbs and Giri 1998; Hobbs 2001).

The repeated plowings to get a good seedbed for wheat increase costs. Currently, tillage represents about one-third of the total production cost. In addition, excessive tillage and poor soil structure create problems for wheat during the first irrigation. When water remains standing in the field because of poor infiltration, oxygen stress delays wheat growth (Hobbs and Giri 1998; Hobbs 2001).

Continuous rice-wheat cultivation has led pests and diseases to build up. The major weed affecting wheat is *Phalaris minor*, which was normally controlled with the herbicide Isoproturon, but in some places this weed has developed resistance to the herbicide (Malik, Gill, and Hobbs 1998).

Water is also becoming a serious problem. In some areas of northwestern India and Pakistan, water tables are declining rapidly as water is pumped faster than it is replenished. In other areas, water tables are rising and leading to waterlogging and salinity.

Transplanting rice is a demanding, labor-intensive technique. Increasing labor shortages during major agricultural operations (planting, harvesting, and threshing) have reduced the profitability of puddled rice and fostered mechanization. The use of tractors and power tillers in Thailand increased by a factor of 6-7 between 1978 and 1993, and similar trends have occurred in India, Vietnam, Malaysia, Indonesia, and Bangladesh (Bakker et al. 2000). Throughout the eastern Indo-Gangetic Plains, small-scale mechanization is increasing, and in the regional as a whole custom operations are more common (Bakker et al. 2000; Hobbs 2001).

* Basmati rice is a long-duration crop that commands a high price because of its particular aromatic characteristics. In some Indian states, like Haryana, more than 40% of the area under the rice-wheat system is planted to basmati varieties (Mehla et al. 2000). After liberalization of the Indian rice market in the late 1990s, basmati rice has expanded into the states of Ghaziabad and western Uttar Pradesh at the expense of sugarcane. Basmati rice is also grown in the Punjab of Pakistan.

Surface seeding is the simplest no-till system. This common practice for wheat establishment in parts of India and Bangladesh has been introduced into the Terai (lowlands) of Nepal. Wheat seed is broadcast either before or after rice is harvested. The key to success is the correct management of soil moisture. Too little moisture results in poor germination and too much moisture causes seed to rot (Hobbs and Giri 1998; Hobbs 2001). In some areas (e.g., Bangladesh), seed is incorporated with a rotavator pulled by a two-wheel tractor, constituting a reduced tillage system rather than a no-till package. In the lower, flood-prone areas of the eastern Indo-Gangetic Plains, this system results in the highest wheat yields because it enables farmers to seed at least one week before no-till and almost one month before conventional tillage.

Mechanized no-till has been tested in Pakistan, India, and Nepal (Hobbs and Giri 1998). This package is more relevant to the higher yielding, more mechanized areas of northwestern India and Pakistan, where generally four-wheel tractors are used to prepare land. The equipment used is a tractor-mounted seed and fertilizer drill with inverted-T openers that place seed directly into the standing rice residues without any land preparation (Hobbs and Giri 1998). Adaptation of this equipment for use with two-wheel hand tractors has started recently (Peter Hobbs, personal communication 2001). The smaller equipment is better suited to eastern areas where fields are small and fragmented.

No-Till for Rice

Research on no-till for rice started in Australia in the 1950s. Hood (1961) and Boerema (1965) showed that rice could be sown directly into a pasture and yield comparably to rice sown after conventional cultivation. Weeds were controlled and pasture was prevented from re-growing through flooding. No herbicides were used.

In the US, methods of crop establishment, weed control, and water and cover crop management for no-till irrigated rice were investigated in the 1980s and 1990s in Louisiana (Bollich 1991, 1997) and California (Williams et al. 1992). Yields of the best treatments were consistently above 9 t/ha. Farmers in Australia and Florida establish about 10% of the rice area using no-till.

Research on no-till for irrigated rice in Brazil started in the 1970s. By the 1990s, irrigated no-till rice had expanded strongly in the southern states. In 1993, an estimated 270,000 ha (33% of the rice area) in Brazil's largest rice-producing state, Rio Grande do Sul, was planted with no-till irrigated technologies thanks to satisfactory weed control, an improvement of the cost/benefit relationship, and a better integration of crop and animal farm production (Sousa et al. 1994).

Despite these advances, little has been done for small-scale rice growers such as those in South Asia. In the late 1990s, the International Rice Research Institute (IRRI) established a long-term study on no-till irrigated rice to address the lack of information on the technology, refine technologies developed in Australia and the US, analyze differing results and lack of follow-up from earlier research at IRRI, and identify systems that could save water and labor (Piggin et al. 2000).

Preliminary results at IRRI suggest that a satisfactory lowland rice crop can be established using no-till seeders mounted on hand tractors. Careful crop establishment and management are needed to avoid problems with rice seedling emergence and survival. Effective weed control can be obtained with glyphosate and adequate water management. Post-emergence weed control (either manual or with a combination of herbicides) is critical. The economic advantage of no-till rice relative to conventionally tilled rice depends on the relative prices of herbicides, labor, and fuel. Wet seeding requires 4-5 tillage operations, seedling propagation, and transplanting. No-till requires one spraying and one sowing operation. At 2000 values, costs were comparable (Piggin et al. 2000).

As with most early research on no-till, the main knowledge gaps in the package for irrigated rice are related to the development of appropriate machinery, weed control, crop establishment, and crop management. A related line of research is the development of practices for growing nonpuddled rice in plots where puddling is not needed (i.e., heavy, poorly drained, lowland, and salt-affected soils) (Bakker et al. 2000).

Nonmechanized no-till has become possible since animal-pulled planters have been produced locally. These implements are still too new to show any impact.

Bed planting, described earlier, is being tested in the region. A local manufacturer in the Punjab of India has built a prototype low-cost planter that plants three rows of wheat on 70 cm beds at the same time that the beds are formed (Hobbs and Giri 1998; Hobbs 2001).

Benefits of no-till in the Indo-Gangetic Plains

The problems affecting rice-wheat systems in the Indo-Gangetic Plains have no single solution. Appropriate economic and agricultural policies can foster diversification of crops and techniques (Kataki, Hobbs, and Adhikary 2001; Pingali and Shah 2001). New technologies that reduce input use (at current prices), such as no-till, nonpuddled rice, and planting on permanent beds, can also help in the transition to a more sustainable agriculture.

Cost savings are substantial with no-till. In a trial with wheat, five irrigations, each at a depth of 8-10 cm, were applied under conventional tillage, whereas only 4 were needed under no-till. Under conventional tillage, on average, between 26 and 34 hours are required to apply two irrigations at pre-sowing and another at the crown root stage (21 days after seeding), costing 1,800 Indian rupees (Rs) per hectare. With no-till, farmers did not apply the pre-sowing irrigation; the first irrigation was applied 4-5 days earlier and took only 8-10 hours, costing about Rs 475/ha (Hobbs and Giri 1998). Savings per hectare with no-till reach up to 1 million liters of irrigation water and about 60 liters of diesel (Melha et al. 2000). No-till has the potential to save 6-10 plowing operations, reducing costs from Rs 825 with conventional tillage to Rs 125 (Hobbs and Giri 1998). By substantially reducing turnaround time between rice harvest and wheat planting, no-till increases wheat yields.

No-till has proven very effective in controlling weeds in wheat because germination of most weeds is triggered by light or by lower temperatures. Since the soil is disturbed less with no-till, less weed seed is exposed and germinates (Hobbs and Giri 1998). Also, through timely planting, wheat can emerge early and shade out weeds. Farmers can use the savings obtained by reducing the number of tillage operations to buy the new, more effective but expensive herbicides and improve weed control (Malik, Gill, and Hobbs 1998). Recent data suggest that no-till reduces weed infestations over time, and eventually no herbicides are required in some seasons (Peter Hobbs, personal communication 2001).

Thanks to the availability of custom machinery services, small-scale farmers have been able to use no-till. By adopting no-till, small-scale farmers obtain two additional benefits: their operating capital requirements fall because they need to contract fewer tractor hours, and they no longer need to maintain bullocks all year on the farm. Often farmers replace bullocks with water buffaloes to obtain additional income from selling their milk. In Haryana in 2001, 70% of farmers that adopted no-till did not own a tractor and used custom services; additionally, 40% of the adopters were small landholders with farms smaller than 2 ha (R.K. Malik, personal communication 2001).

Constraints to the adoption of no-till

The main constraints to farmers' adoption of no-till for wheat are imperfect drill performance and some shortcomings in the no-till package. Additional factors are lack of knowledge and information about no-till and skepticism among extension and scientists about no-till.

Issues related to the no-till drill. Cost does not appear to be a constraint to the adoption of the drill.[33] More important factors behind the limited demand seem to be technical limitations and current extension policies.

The drills have several technical limitations. First, the openers are fixed to a bar and cannot follow the contour of the soil. If the field has not been leveled, some of the seed is not placed at the proper depth. Second, the drill lacks a compacting mechanism behind the openers, so in heavier or damp soil some seeds do not make good contact with the soil. Some farmers overcome

[33] Drills currently cost about US$ 300 in India and US$ 600 in Pakistan. (The difference results from different input prices in both countries and slight design dissimilarities.) During the fieldwork for this report, farmers who already owned equipment mentioned that they would buy a better but more expensive drill. Nor does the price of the drill seem to be a deterrent for small-scale farmers who do not invest in machinery and rely on custom services.

the problem by planking or by irrigating after seeding.[34] Third, the inverted-T openers do not perform well if there is loose straw because they work as a rake.[35] Fourth, if the drill is not properly calibrated, up to 15% of the seed is broken. Finally, most farmers find it difficult to regulate fertilizer and seed flows in the drills.

The last two problems have been solved in the latest version of the drill developed by a manufacturer in Amristar, India, but other manufacturers have not yet adopted the changes. In a recent survey conducted in Punjab by the National Agricultural Research Center (NARC) of the Pakistan Agricultural Research Council (PARC), 70% of farmers pointed out operational problems with the drills. Even though some of the problems could result from inappropriate training, the field research for this report confirmed the design shortcomings. Farmers mention that obtaining customer support from manufacturers and finding local technicians to repair the drills are also major problems. As the equipment industry develops, these issues should be resolved.

Extension policies in India and Pakistan make the drill available without cost to farmers in targeted villages for limited periods. Although the drills are lent for three years at most to each village, farmers expect to use them for the foreseeable future. Some farmers indicated that they would buy a drill if they could not get one for free. Also, for almost four decades, government officials, researchers, and extension agents in both countries have assumed that subsidies are needed to promote new technologies, and farmers expect to receive them. The state governments of Haryana and Punjab, India, subsidize up to 30% of the price of the drill; farmers in other states are waiting for similar subsidies.

In recent years, demand for no-till drills has increased faster than supply, to the point that manufacturers cannot cope with demand. Several new factories have started producing drills, but the quality of these new entrants is uneven. In the medium-term this should not be a problem since the market will eventually weed out the lowest quality manufacturers.

Issues related to the package. The main problems of the package currently in use are weed management (especially for rice), residue management, a lack of profitable rotations, insufficient command of the package by local extension agents and researchers, and insufficient training of farmers.

The lack of an effective weed management package, especially for rice, is a major barrier to the adoption of permanent no-till.[36] Weed management should integrate alternative herbicides with mechanical, cultural, and agronomic practices. The herbicides currently available are not very effective against several weed species, especially those that compete with rice. Agrochemical companies are active in the region but do not participate actively in the development of no-till packages, a point that will be discussed in greater detail later. Weed management could be improved through integrated weed management strategies that include rotations with other crops; researchers at the Regional Research Station of Haryana Agricultural University in Karnal found that introducing sugarcane after the rice-wheat sequence greatly reduced weeds in the subsequent rice crop.

Three problems prevent good residue management. First, livestock compete with no-till for the use of residues. Second, the drill is less efficient with the loose residues left on the soil after combine harvesters have been used.[37] The regional importance of this problem will become more acute as combine harvesting increases in response to labor shortages. Currently farmers remove or burn all loose residues. Although extension agents discourage this practice, there are no alternatives except to incorporate the residue into the soil. Third, as mentioned previously, irrigated rice produces large amounts of residue that, when left in the field, hinder germination of the subsequent crop. Since wheat has to be planted as soon as possible after rice, farmers cannot wait for the rice straw to decompose.

[34] Apparently, in heavy soil closing the slit opened by the drill reduces germination (Peter Hobbs, personal communication 2001). However, during the field visits farmers complained about the open slits.

[35] Loose straw results from combine harvesting, land preparation, or grazing of the standing rice stubble after harvest.

[36] The problem is more relevant for direct seeded, nonpuddled rice than for transplanted rice on beds.

[37] Researchers are developing equipment that can operate with loose residues, including chopping and spreading the straw as it leaves the combine or after, and a drill that can plant into residues (Peter Hobbs, personal communication 2001).

Economic policies that make the rice-wheat sequence the most profitable option have hindered the introduction of alternative rotations (Pingali and Shah 2001). These policies started to change in India in 2000, and farmers are actively trying alternatives. Most researchers, on the other hand, are still focused on the rice-wheat system. One of the major hurdles for diversification is the lack of markets for alternative crops. Even though markets could develop on their own, adequate policies could ease and accelerate the transition.

Another difficulty is that many researchers and extension agents in the region still do not interact effectively. Extension agents learn how to operate the drill but not about other components of the package, such as weed control. For example, at a state university a farm machinery professor who demonstrates no-till to farmers mentioned that, even though he knew weeds could be controlled chemically, that was the expertise of weed specialists. For fields with severe weed infestations he recommended mechanical control with a rotavator instead of no-till.

There are indications that farmers do not receive proper training in using the drill. In the survey conducted by NARC, about 20% of farmers who had bought a no-till drill still plowed the field before sowing, and more than half were not trained to operate the drill. In the field interviews conducted for this report, many farmers complained about difficulty in calibrating the drill, whereas more experienced users found no problem. Similar training deficiencies were observed with respect to herbicide use.

Development of no-till for wheat in the Indo-Gangetic Plains

The development of no-till packages in India and Pakistan followed different paths. In India, a few researchers at state universities conducted research, but except in Haryana and Punjab, extension did not join these efforts. In most states, the Rice-Wheat Consortium (RWC) for the Indo-Gangetic Plains coordinated research and extension for no-till.[38] In Pakistan, research was conducted initially by NARC in partnership with CIMMYT, whereas extension was conducted almost exclusively by the On-Farm Water Management Wing (OFWM) of the Department of Agriculture, Government of Punjab. In both countries, interactions between research and extension agencies are limited.

First CIMMYT and later the RWC provided important research support. In 1999 the RWC started an important program in India and Pakistan to study alternative methods for rice establishment. The International Center for Research in the Semi-Arid Tropics (ICRISAT) has also joined the network by providing improved seed of several leguminous crops, mainly chickpea. Although researchers and manufacturers from both countries interact with colleagues and farmers within the country, knowledge of developments occurring in neighboring countries is limited. The RWC has organized several traveling workshops to address this deficiency, but their impact has been limited. Knowledge of developments outside the Indo-Gangetic Plains is restricted to a handful of researchers, mainly from international organizations.

Another issue is that most researchers have accepted no-till only recently. In a 1996 workshop in Haryana on long-term soil fertility issues in the region, several soil and crop management techniques were discussed, but no-till did not feature among the recommendations (Abrol et al. 1997). Adoption of no-till by farmers in the Indo-Gangetic Plains is also a recent and localized phenomenon. Even in 1998, Hobbs and Giri (1998) reported that adoption was scant. It is estimated that the wheat area planted with no-till in 2001 will reach 50,000 ha in Haryana, 10,000 in Uttar Pradesh, and 5,000 ha in the Punjab of India. Adoption in other Indian states has been more limited. Adoption in the Punjab of Pakistan was estimated at 30,000 ha for 2000/01.

Pakistan. In the 1970s, Massey University (New Zealand) established a collaborative program with Pakistan, through which several Pakistani agronomists pursued doctoral studies

[38] The Rice-Wheat Consortium (RWC) was established in 1994 as an Ecoregional Initiative of the Consultative Group on International Agricultural Research (CGIAR), involving the national agricultural research systems of South Asia, international agricultural research centers, and advanced research institutions. Funding for the RWC comes from many sources, including the participating countries; the Governments of Australia, the Netherlands, UK, and the US; the International Fund for Agricultural Development, the Asian Development Bank, and the World Bank. The activities of the RWC are decided on and approved by the steering committee chaired by the heads of the four national agricultural research systems on a rotating basis. CIMMYT currently acts as the convening center of the Consortium on behalf of the steering committee and the CGIAR.

related to no-till. Among them was Ashraf Choudhary, who visited Pakistan in 1982 to promote no-till under a UNDP-funded assignment. He brought literature and two inverted-T openers developed in New Zealand by Aitchison Industries, which were passed on to Peter Hobbs, a CIMMYT wheat agronomist based in Pakistan. The openers were mounted on a frame and tested at the Agricultural Machinery Division of NARC. Interactions with NARC were good because the center had just been created and the researchers were eager to cooperate.

Hobbs used funding from the US Agency for International Development (USAID) to circumvent traditional public-sector regulations and make the network more agile. In 1984 he imported an Aitchison drill into Pakistan with financial support from USAID and tried it with NARC. Assuming that farmers would not abandon their late-maturing rice varieties, researchers focused on reducing turnaround time so that wheat could be planted earlier. The first no-till work occurred in farmers' fields. Even though farmers were convinced by the results, the New Zealand drill was still too big and too expensive for Pakistan.

From his base in New Zealand, Choudhary continued to promote no-till in Pakistan with NARC and PARC between 1985 and 1991. In 1988, Hobbs obtained additional funds from USAID to make 20 copies of the Aitchison drill, which were used by NARC used until the early 1990s. NARC researchers convinced the extension services to conduct a few no-till demonstrations, but the extension service lacked funds to keep the drills in working order, and they deteriorated rapidly. The demonstrations failed and the technology was not recommended. After Hobbs moved to Nepal in 1988 (where he assumed regional responsibilities, including work with the RWC) and Choudhary shifted the focus of his work to Iran in 1991, all promotion of no-till in Pakistan came to a halt.

During the mid-1990s, the OFWM in Punjab had also tried no-till, but the results were not convincing. In 1997, Choudhary invited Mushtaq Gill, OFWM Director General, to visit Massey University and see no-till in operation. In 1998 Gill participated in a traveling seminar organized by the RWC that made him confident about the potential of no-till. Gill realized that no-till could save substantial amounts of water and instructed his staff to promote it. OFWM had a large network of extension agents that interacted with irrigation associations at the village level; this contact with farmers enabled OFWM to establish a large number of demonstrations. In 1998, Hobbs was introduced to Gill, and they started collaborating on a package for Pakistani conditions. OFWM collected the old no-till drills and started to promote no-till aggressively. The OFWM in collaboration with the RWC contacted local drill manufacturers and convinced them to start production of the drill that had been developed in India. As noted, collaboration with local extension and research agencies remained weak (although Choudhary continued to provide assistance). Even though NARC supports the research done by OFWM, the research effort is limited. Extension agents conduct on-farm trials with active support from the RWC and more limited interactions with NARC.

The Government of New Zealand continued to support the diffusion of no-till in Pakistan in the 1980s and 1990s, financing several graduate students and, more recently, research and dissemination programs. Two other important sources of funds for research on no-till were DFID and CIMMYT.

The OFWM has supported the creation of an association of no-till farmers, but its presence in the field is small. The Pakistani association has not organized a network like those in South America to generate and disseminate information.

India. Research on no-till for wheat in India started almost three decades ago (Aslam et al. 1993; Brar et al. 1983; Verma and Srivastava 1989, 1994; Verma, Srivastava, and Verma 1988). Several state agricultural universities tried no-till in the 1970s but their efforts were marred by technical problems. Lacking adequate planting equipment, they planted seed manually; chemical weed control was also difficult. This line of research was soon abandoned by all except a handful of researchers working in isolation.

In 1990, Hobbs introduced the inverted-T openers to Indian researchers. In 1991, engineers at G.B. Pant University of Agriculture and Technology, Pantnagar, modified the traditional *rabi* (cool season) seed drill by replacing the old seed coulters with inverted-T openers (Hobbs and Giri 1998; Melha et al. 2000). The researchers contacted several local shops to produce the drill commercially, but none were interested in starting a new line of production for which they saw no market. Eventually they found a manufacturer in Punjab who was willing to start production.

In 1993, S.S. Dhillon of Punjab Agricultural University participated in a wheat agronomy course managed by Ken Sayre at CIMMYT headquarters in Mexico, where he became acquainted with bed planting. Upon his return to India, he tried this technology on wheat with the objective of reducing production costs. To his surprise, infestations by *Phalaris minor* were greatly reduced, and the incidence of this weed decreased over the years as no-till was used.

In 1994, R.K. Malik attended the same course in Mexico. Malik, a weed scientist at Haryana Agricultural University, was also an advisor to the university's Vice Chancellor. Malik was able to explain the benefits of no-till and, through his position, managed to get the university to promote it. To overcome bureaucratic barriers, the RWC bought several drills and donated them to the university, which contributed extension agents and their expenses. The rapid adoption of no-till in Haryana was the consequence of a concerted effort by state researchers and extension agents, the state subsidy for purchasing drills, and farmers' agricultural practices. Since a large proportion of farmers grew long-duration Basmati rice, wheat was usually planted late. The benefits of no-till came not only from cost reductions but also from higher wheat yields.

Recently, the University of Adelaide (Australia) started a program with Haryana Agricultural University to control *Phalaris minor*,further develop no-till, and foster adoption.

In Punjab, three factors have delayed adoption. First, researchers and extension agents often gave conflicting advice. Second, farmers planted rice that matured more rapidly than the varieties grown in Haryana, so the benefits of no-till were smaller. Third, in Punjab, recommendations have to be approved by the state university before they can be taken to farmers. This meant a delay in getting farmers to experiment and become convinced about the technology. In 2001 the state government introduced a US$ 70 subsidy for the purchase of no-till drills.

Agrochemical companies collaborate with the state universities, but not with the RWC. In the late 1990s Monsanto supported no-till research at the universities but soon reduced its activities: the potential market for glyphosate was small because it could not control *Phalaris minor* efficiently. Even though other herbicides are used in the region, agrochemical companies have not played a major role in developing no-till.

Case 5: The Ghanaian Experience

In 2000, an estimated 100,000 Ghanaian farmers used no-till on 45,000 ha (Ekboir, Boa, and Dankyi, forthcoming). Because small-scale farmers in Ghana traditionally practiced bare no-till, the no-till package developed for Ghana consisted only of weed and stubble management practices. The similarity of the traditional and no-till packages favored adoption while the lack of appropriate planters has prevented mechanized farmers from adopting this technology.

The earliest research on no-till in Ghana started in the late 1960s (Ofori 1973) and was continued in the 1970s by local researchers who interacted little with other agents, including agrochemical companies and foreign researchers. Their findings showed the beneficial effects of no-till on soil and water conservation (Mensah-Bonsu and Obeng 1977).

In the 1990s, no-till research was concentrated in the Crops Research Institute (CRI) in Kumasi and the Ghana Grains Development Project (GGDP).[39] Roberto Soza, a CIMMYT agronomist working with the GGDP, organized no-till research from 1990 until 1996. In 1991, the GGDP adopted the no-till system for planting maize and grain legumes on five research stations. The system was tested extensively in farmers' fields across the country.

In 1993, Sasakawa-Global 2000 (SG 2000)[40] and Monsanto joined the GGDP and the extension service from the Ministry of Food and Agriculture to promote no-till. The program received strong political support from

[39] The Ghana Grains Development Project involved the Crop Research Institute, the Grains and Legumes Development Board, the Ministry of Food and Agriculture, CIMMYT, and the International Institute of Tropical Agriculture (IITA). It was funded by the Government of Ghana and the Canadian International Development Agency.

[40] Sasakawa-Global 2000 is an NGO financed by the Government of Japan.

the government (Findlay and Hutchinson 1999). The results obtained by the researchers were used to train the extension agents, who carried out their own demonstrations in farmers' plots. Monsanto helped CRI evaluate the efficacy of powder glyphosate in small packages for no-till on farmers' fields with maize and beans. Trial protocols and guidelines were established by Monsanto and discussed with CRI researchers, who implemented the trials with financial support from SG 2000. Even though the powder presentation was more expensive per unit of active ingredient than the liquid formulation, farmers initially preferred it because it was the exact amount they needed for one backpack sprayer. After farmers became familiar with the no-till package, they started to demand glyphosate in larger, cheaper presentations.

This program established demonstration plots large enough to show the advantages of no-till under farmers' conditions; other activities included pre-season farmer training, on-farm demonstrations, field days, field tours, workshops and seminars, and distribution of fact sheets and production guides. The program did not promote weed control alone but rather an entire farm-management system that encompassed the use of certified seed, fertilizing at planting and as a top dressing, pre-planting weed control with herbicide, manual or chemical in-crop weed control, and new harvesting techniques that left crop residues in the field. Farmers were involved in implementing demonstrations, from site selection through herbicide application to harvesting. Demonstration plots were situated at strategic points—along major footpaths and roads linking villages / towns as well as on highways (Findlay and Hutchinson 1999).

The diffusion program established links with the Sasakawa Center at the University of Cape Coast, making it possible for agricultural students in their final year to view farmers' no-till fields at the end of their soil conservation course.

From an institutional point of view, the research effort (measured by the number of researchers and public resources committed) was quite limited. Even in 2000, public research institutions had no formal programs on no-till. In contrast, the few researchers actually doing the research were extremely motivated and innovative. The overall research program may have been weak, but a strong extension program was implemented. Extension agents and researchers at CRI work closely together with a participatory approach, to the point that farmers cannot distinguish the activities of each group. Some rural banks and district assemblies also promote no-till by providing credit to selected farmers.

After a hand-operated no-till maize planter was imported from Brazil by SG 2000 and proved a success, no-till researchers approached engineers at CRI to have it copied, but they showed no interest. Unlike other countries (Brazil, India, and Pakistan), in Ghana local craftsmen were not approached to copy the planter. Research in Ghana did not dedicate a substantial effort to developing planters and mechanized sprayers because of the weak research effort and because most farmers in central Ghana did not use planters. As a result, adoption of no-till in Ghana has been restricted to small-scale farmers, while large-scale mechanized farmers continue with conventional tillage.

Case 6: The Paraguayan Experience

The Paraguayan agricultural sector traditionally has been characterized by the prevalence of small-scale, subsistence farmers, who occupy only 6% of the land but produce 35% of the agricultural output (Sorenson et al. 1998). In the late 1970s, the government opened forested areas in eastern Paraguay to agriculture and promoted the settlement of immigrant farmers and small-scale farmers from Paraguay's Central Region. Most of the immigrants originated in southern Brazil and came with a great deal of no-till experience. Since the newly cleared areas of Paraguay were ecologically similar to the Brazilian state of Paraná, many Brazilian technologies could be adopted without modification. The immigrant farmers interacted closely with farmers and researchers in Brazil.

In the 1980s, the Japanese International Cooperation Agency (JICA) mounted a research program in Paraguay to support the country's important community of Japanese farmers. One of JICA's activities was to import no-till planters. Even though the farmers used the planters, they still burned the straw because residue management practices had not been developed.

In the early 1980s, local cooperatives started no-till validation programs. After moving to Paraguay in 1988, Pat Wall fostered interactions between Paraguayan farmers and farmers' associations and Argentine and Brazilian associations of no-till farmers. Wall also worked with researchers from a public institution, the Centro Regional de Investigación Agropecuaria (CRIA), to create a no-till program.

One precursor of no-till programs for small-scale farmers was the introduction of green manure crops in the Edelira region by the public extension service in 1989. In 1990, GTZ, in association with the Ministry of Agriculture (MAG), started to promote green manure crops among small-scale farmers, but the level of adoption is not known.

Since 1993 the Soil Conservation Program, involving MAG and GTZ, has encouraged no-till among small-scale farmers in five pilot areas, especially Edelira and San Pedro (Sorenson et al. 1998). The program supported extension agents and provided some no-till machinery, but the key factors in the diffusion of no-till among small-scale farmers were two highly motivated extension agents, Magin Meza and Elba López de Meza, who built an effective partnership with farmers. After two years of working on green manures, they convinced a group of small-scale farmers on the brink of bankruptcy to try no-till. In the following years they jointly developed an appropriate no-till package. Six years after starting with no-till, the farmers had completely turned around their financial situation, reduced their dependence on soybeans and cotton, increased their total income, and reduced income variability. Costs fell due to lower labor and machinery requirements, which also reduced the need to take expensive short-term credit. Net farm income increases of 35-236% have been reported among no-till adopters (Sorenson et al. 1998). These changes resulted in higher living standards, including improved housing, vehicle ownership, and university education for children.

The MAG-GTZ program supported the formation of a no-till association among small-scale farmers in Edelira, but its impact has been limited. Committees from the association received no-till equipment from the GTZ project or from the local government, but demand for the equipment is too high and sometimes farmers cannot use it when needed. At other times, the shared equipment is not maintained properly (Sorenson et al. 1998). One of the main benefits that large-scale farmers obtained from their no-till associations was the gathering and generation of information. Small-scale farmers, however, do not have resources to search for information by themselves. These resources include access to technical literature (through publications or the Internet), travel to distant sites, and setting up a trial network. A market for no-till custom seeding operation for small-scale farmers has not developed because the large-scale farmers who own the machinery are located in different regions (Rolf Derpsch, personal communication, 2001). Research was greatly strengthened when GTZ opened a program in Paraguay in late 1988, transferring Derpsch from Brazil. Work initially focused on large- and medium-scale farmers, but in 1999 a program for small-scale farmers was implemented.

Today, a Paraguayan Association of No-till Farmers and local cooperatives interact with the GTZ program and Brazilian institutions to adapt no-till technologies to local conditions. There is an active exchange of information between farmers' associations from Brazil, Argentina, and Paraguay. The members of the Association of No-till Farmers are large- and medium-scale farmers; small-scale farmers do not participate because they face different problems and consequently need different solutions (for instance, unlike small-scale farmers in Brazil, those in Paraguay use different cover crops).

It is estimated that in 1999/2000, no-till was used on one million hectares. Despite widespread use of no-till on medium- and large-scale farms, adoption by small-scale farmers is just starting. Wall (1998) and Sorensen et al. (1998) estimated that the area under some type of no-till on small farms in 1997 was about 4,500 ha, but the area under permanent no-till was less than 2,000 ha and involved less than 150 farmers scattered around the towns of Edelira and San Pedro, located in eastern and southeastern Paraguay, respectively.

Key Factors for Developing No-Till Packages for Small-Scale Farmers

As the case studies have shown, no-till is a complex technology in which several components must be adapted to local conditions. Because of this complexity, a single agent cannot develop a package; what is needed is a network that may include researchers, input suppliers, equipment manufacturers, NGOs, extension agents, and farmers, among others. Networks are also necessary for diffusion. Individual agents (e.g., researchers or input suppliers) have researched no-till in many countries, but substantial adoption (by large- and small-scale farmers) has occurred only when an innovation network emerged.

The composition and evolution of innovation networks have varied across countries and times in response to local technological needs, the different agents active in each region, and the socioeconomic environment. What are the key factors and problems that have influenced the performance of no-till networks? They include those identified in traditional analyses of lack of adoption of modern technologies: market failures or missing markets.[41] In addition to these problems, the literature on innovation highlights system failures—that is, failures in the innovation networks caused by barriers to collaboration among agents.

Key factors

The resources that determine the performance of innovation networks are the particular agents active in different environments, their core and complementary assets, and learning routines.

The most important role in no-till networks is that of the catalytic agent. In the case studies reviewed in this report, this role was played in Brazil initially by agrochemical companies and later by farmers' associations. In Ghana, the catalytic agents were Monsanto and SG 2000; in India, CIMMYT and the RWC; and in Pakistan, CIMMYT, the RWC, and the OFWM. CIMMYT is trying to organize similar networks in Bolivia and Mexico, while GTZ is active in Paraguay.

The core assets contributed by the catalytic agents described in this report were participatory research methodologies, information exchanges among participating agents, linkages with international information sources, and funds. The funds served three purposes: they allowed other agents (in particular, public researchers and extension agents) to participate in the network; in some countries they were used to purchase the first no-till equipments, (creating the demand); and they allowed farmers to experiment with the technology.

Only the Brazilian network has evolved into a diverse network in which several agents play catalytic roles in their regions, and local and foreign agents generate multiple information flows. In the other networks reviewed in this report, information flows converge on the catalytic agent, who distributes the information to other agents (sometimes in the form of regional workshops or study tours) and also serves as the main link with foreign sources of information.

In addition to supporting research, the catalytic agent often provided funds to accomplish two important objectives: the development of planters and the organization of extension. The early development of no-till machinery is potentially hampered by the lack of demand for specialized equipment. Since farmers are not sure about the benefits of the technology and the quality of the initial technical standards, they are reluctant to buy the equipment. At the same time, manufacturers are unwilling to invest in developing the equipment because demand is lacking and it is difficult for them to protect their discoveries. In Brazil, this hurdle was overcome by the collaboration between ICI, EMBRAPA-CNPT, and Semeato. ICI and EMBRAPA-CNPT lowered development costs by importing foreign prototypes and by contributing formal research capabilities, while Semeato added their production lines.

In Bolivia, planters were developed through collaboration between CIMMYT, PROTRIGO, the local university, and the SILSOE Research Institute; in the Indo-Gangetic Plains, the agents were CIMMYT, universities, and local manufacturers. In both cases, the networks reduced the development cost and created the initial demand, reducing uncertainty for manufacturers. In Brazil, ICI lent imported machinery to interested farmers. In Bolivia and the Indo-Gangetic Plains, the no-till programs bought a few drills and lent them to farmers. In all cases, interest was created among farmers by allowing them to experiment with the planters after the demonstrations.

The contribution of extension infrastructure took different forms. In Brazil and Ghana, agrochemical companies provided the initial

[41] Market failures arise when the market cannot value the consequences of the actions of one agent over other agents (externalities), when one participant in a transaction has more information than the other (asymmetric information, also known as moral hazard), or when certain goods do not have a market value that reflects their production cost (public goods).

resources for the extension effort, either using their sales force or funding public agencies. In other cases, resources for extension came from the public sector; in India, for example, state universities provided the extension infrastructure; in Pakistan, it was the OFWM.

Farmers played an important role in organizing no-till networks in South America, but in most cases, farmers have remained nonleading partners in research and/or extension activities. Farmers' associations played a major role in the diffusion of no-till for medium- and large-scale farmers in Brazil, Paraguay, and Argentina; only in southern Brazil were these associations important for small-scale farmers. Attempts to create similar associations in other countries have not been successful. The South American associations succeeded because they were created by small groups of highly motivated farmers with resources to search for, produce, and disseminate information.[42] The associations were very focused and efficient in these activities, and they enabled farmers to benefit from the economies of scale that characterize these processes. Associations of small-scale farmers were not successful because such farmers lack resources to generate and/or gather information. When small-scale farmers have successfully adopted no-till, other institutions (e.g., agrochemical companies, NGOs, farmers' associations, international centers) were the sources of information. The extension programs for small-scale farmers had a more traditional structure than those for large-scale farmers.

Even smaller and more focused associations, such as those for purchasing and sharing machinery, have seldom worked for two reasons. First, the seeding period has to be long enough to allow all members to plant on or very close to the optimal date. Second, there is a free rider problem:[43] not all association members maintain or calibrate the planter properly. When these associations have worked, a catalytic agent set and enforced the rules of use.

It is important to make a distinction between public research institutions and the individual researchers who work within them. No institution (except for IAPAR and EMBRAPA-CNPT) has ever played a major role in the early development of no-till or in the organization of a no-till network. Research institutions have been slow to recognize new areas of research that cannot be described along disciplinary lines or directed toward specific crops; this difficulty has become more prominent as institutions have been forced to generate an increasing share of their funding and have introduced more formal priority setting procedures. On the other hand, many researchers from public institutions, working individually, have been involved at different stages and in different ways in generating no-till packages. They contributed formal research capacity and scientific information from their fields of specialization. Despite this involvement, they did not become the hub of the innovation network because they lacked financial resources and, in many cases, a participatory approach to research.

Agrochemical companies provided important support for the development of no-till packages in countries and regions with potential markets for their herbicides. Their contributions involved conducting in-house research, funding research and extension by third parties, and exchanging information. Even in their high-priority countries, however, these companies have not had a uniform impact. In some countries, such as Brazil and Ghana, private companies were closely involved in organizing the network and contributed key assets. In other countries, such as Mexico and India, agrochemical companies shared the public institutions' linear vision of science and could not catalyze no-till networks despite important investments.

Equipment manufacturers have been less innovative than agrochemical companies in generating information and machinery because they have fewer resources for research, their ability to capture research benefits is limited,[44] and the potential market is smaller. Manufacturers receive information from a number of sources, including local farmers, public institutions, agrochemical companies, and international research institutions.

[42] They could pay for travel in their countries and abroad, hire consultants, and experiment on their own farms.

[43] The free rider problem arises in a network because each member can increase his individual benefits if he contributes to the common effort less than is expected from him. Since this is true for every member, in the absence of a mechanism that forces everybody to contribute his expected share, the collective effort and benefits are smaller than when the rules can be enforced.

[44] Patents have never been important for agricultural equipment manufacturers and are almost impossible to enforce in most developing countries.

The most sophisticated manufacturers, like those in Argentina or Brazil, actively follow developments in industrialized countries by visiting farm shows in the US to copy advanced designs. Conversely, US manufacturers copy innovations developed in South America. Manufacturers in most other developing countries rely on information provided by agents with international links, such as international research centers or agrochemical companies.

Numerous NGOs and international cooperation agencies (especially GTZ) have played important roles in the evolution of no-till in many countries, providing funds, research staff, and information. Their impact has been limited, however, except for a few cases, as in Ghana.

With the exception of CIMMYT, most international agricultural research centers of the Consultative Group on International Agricultural Research (CGIAR) have had limited participation in no-till networks. The International Institute for Tropical Africa (IITA) has maintained a no-till program in Africa since the 1980s, and the International Center for Research in the Dry Areas (ICARDA) has studied tillage methods for several years (Pala 2000). These programs have produced a wealth of information, but their impact has been circumscribed because they were based on traditional experiment station or on-farm research. Recently IRRI initiated a program on no-till and began to participate in the Indo-Gangetic Plains no-till network. ICRISAT has had limited participation in no-till research in the RWC and in Africa.

Most local universities, as institutions, have been absent from no-till networks in developing countries. Professors are not required to interact with farmers, and there is no effective quality control of their activities. These features, combined with insufficient resources for research and interaction with foreign institutions, have prevented professors from staying up to date in their disciplines. Most professors have been reluctant to change research and teaching approaches developed over many years.

Foreign research institutions and farmers, on the other hand, have generated no-till information that is useful to local agents. The activities of advanced research institutions are particularly important, because they perform science-intensive research that in many cases can be transferred to developing countries. These institutions have mostly interacted with researchers linked to international research centers or multinational companies, although some have recently established collaborations with farmers' associations or public institutions in regions where no-till networks have emerged.

Several international networks have been created in the last decade to foster the development of sustainable agriculture. Even though no-till is one of the most important technologies recommended, other packages are also promoted (see "Networks for Sustainable Agriculture," p. 36).

System failures

The existence of market failures (in particular, the prevalence of public goods) has been the traditional justification for the public sector's involvement in research. The recent literature on NIS highlights a new area for public policy: system failures that arise from insufficient interaction among agents. In the case of the networks that generate no-till, such system failures include difficulties in broadening the focus of existing networks, poor understanding of the particularities of no-till research, the linear vision of science that still prevails in most public research institutions, lack of a systemic approach to the analysis of production systems, contradictory reforms of public research institutions, and restrictive frameworks of funding agencies.

Difficulties in broadening the focus of existing networks. In all cases, except in South America, no-till research has not focused on developing a complete package (keeping the soil covered, minimizing soil disturbance, and practicing crop rotations). Usually only some of the required components were developed, such as weed management strategies or machinery. To develop the missing components, the network must be enlarged to acquire new complementary assets. In many cases, local agents can contribute those assets, but their participation is restricted by inter-institutional rivalries or by working in an organizational structure that reflects a linear vision of science. In other cases, foreign agents hold the needed complementary assets, and their participation is expensive. Because of weak interactions with foreign agents, many local researchers do not fully understand the deficiencies in the packages being promoted. Consequently, they fail to recognize the need to incorporate new complementary assets into the network or to identify the owners of those assets.

Poor understanding of the particularities of no-till research. Because no-till is a relatively new technology, the mechanisms for developing and diffusing information are not well established. One of the main roles of the catalytic agents is to establish those mechanisms by identifying the weaknesses of their networks and the agents that can help to overcome them. This nontraditional approach to the development of agricultural technologies requires new awareness on the part of the catalytic agents and continuous assessment of the network. Agents must interact more closely and informally than in networks aimed at developing better known technologies. The novelty of this institutional framework makes it more difficult to obtain institutional support and funding for many of these activities compared to more traditional research programs.

Public research institutions were (and most still are) organized on the basis of a linear vision of science. This organizational structure does not provide incentives for researchers and technology users to interact. Researchers plan their activities with little formal (and in many cases ineffective) interaction with extension agents and farmers.

The linear vision of science does not emphasize a systemic approach to the analysis of production systems. Given that many public research institutions are still organized on the basis of disciplines or crops, researchers are accustomed to working in projects specific to their areas of expertise. No-till research requires interdisciplinary collaboration and a systemic (versus commodity) focus, but incentives generally discourage (or at least, do not encourage) participation in interdisciplinary programs.

Public research institutions in many countries are going through a transformation, but the objectives and instruments are often contradictory. The main features of this transformation in research institutions are 1) new priority setting mechanisms (usually relying on more formal procedures and greater emphasis on identification of technology demands), 2) an emphasis on diversifying funding sources, which in all cases included a substantial reduction in direct budgetary allocations, 3) greater pressure to generate resources by selling goods and services, 4) reductions in research staff and support personnel, and 5) serious reductions in investments, which resulted in a general decay of research equipment and outdated libraries. There is evidence that research capability has diminished through the lack of operational funds

Networks for Sustainable Agriculture

CIMMYT recently created a global program on conservation tillage to exchange information on agronomic issues and exchange machinery for small-scale farmers. The bed planter developed in Mexico, as well as the drill developed in Bolivia, were sent to India and Pakistan, where they were further refined and returned to their countries of origin. A CIMMYT-CIRAD project is organizing the exchange of information on planters between Mexico and Brazil. CIMMYT scientists participate in the networks in the countries where they work, visit countries where no-till programs are being implemented, and sustain an active dialog with each other on technical issues.

At Cornell University, the Management of Organic Inputs in Soils of the Tropics (MOIST) group collaborates with partners in Africa (West Africa and Madagascar), Asia (Philippines, Indonesia, and China), South America (Brazil and Paraguay), and Central America (Honduras and Costa Rica). Following MOIST-organized workshop on cover crops and organic inputs in tropical soils, a consortium was formed to address information-access issues synergistically. MOIST also maintains an electronic network, several electronic discussion groups, and three databases.

The Indigenous Fallow Management Network, housed at the International Centre for Research in Agroforestry (ICRAF) in Bogor, Indonesia, comprises Southeast Asian organizations.

The World Bank and FAO have promoted and financed several networking activities, including workshops and study tours by farmers, researchers, and manufacturers from Africa and Asia. FAO also supports international meetings on no-till. The participation of these institutions in networks has been, for the time being, restricted to isolated activities.

and investment. Greater pressure on public research institutions to generate their own resources has forced them to concentrate on producing goods that have a market value—with a reduction in the production of "public goods"—or on research that responds to political needs with very short-term objectives (IDRC 1997; Rozelle, Pray, and Huang 1997; Ekboir and Parellada 2000a).

The linear vision of science restricts activities of funding institutions. Most funding institutions do not understand the importance of fostering interactions among innovative agents and give priority to more traditional research activities. This approach restricts the availability of funds for networking.

Condusions

In areas where adequate no-till packages have been developed, no-till has had a major, positive impact on the lives of small-scale farmers and on the management of natural resources. Developing such packages has not been easy, because novel approaches to research and extension are required. These lessons are important, not only for no-till but for other complex technologies. The range of complex technologies, and the need for them, is expanding as farmers are pushed into globalized markets and increasingly required to integrate production and marketing strategies. Since farmers now have to learn to produce and sell in ever-changing markets where competitors are permanently searching for new strategies to increase their competitiveness, formerly simple technologies (e.g., designed for crop production for local markets) are being transformed into complex technologies by foreign competition in domestic markets. The challenge is far greater for small-scale farmers, who lack resources to search for new economic and technological opportunities.

This expanding universe of complex technologies demands more sophisticated agricultural and scientific policies. A discussion of some of the economic and innovation policy changes required in this new environment may be found in OECD (1999). Less understood are the new policies required to accelerate technical change among small-scale farmers. These policies should be based on the recognition that complex technologies and their adoption are social processes that result from the co-evolution of innovation networks and the technological packages they develop, restricted by technical, economic, and social factors. Several other factors condition policy design:

- *The complexity of the package*—Simpler packages are easier to develop and/ or transfer than more complex packages, because adaptations of complex packages require the involvement of more agents and, potentially, more complex research.
- *The scientific base of each component in the package*—Modification of science-intensive technologies requires strong research institutions (either public or private). Conversely, lay users can modify technologies that do not depend heavily on science.
- *The sensitivity of the package to local conditions*—Drip irrigation can be immediately transferred because its dependence on the local environment is very small. The success of a crop rotation, on the other hand, depends to a great extent on local soils and climates.
- *The importance of commercial inputs*—When a commercial input is a key component of a technology with a large market potential, its producer has a strong incentive to invest in the development of the whole package, even though a large part of it could be a public good.

Although the development of no-till packages and their adoption by small-scale farmers followed different paths than for large-scale farmers, the paths shared one important common feature: all successful programs resulted from networks that worked with participatory research approaches (for a partial list of some recently established networks, see p. 36). Large-scale farmers had the resources to create novel institutions and to search for information; small-scale farmers, lacking those resources, relied on other agents to organize no-till programs. Other characteristics of the successful development and adoption of no-till for small-scale farmers are listed below.

- A catalytic agent was willing to mobilize others to organize programs for small-scale farmers. The catalytic agent took different forms: private companies, associations of large-scale farmers, state governments, agronomists international research institutes, in or international cooperation agencies.
- Although the most active agents in the network were not small-scale farmers, they were willing to develop or adapt existing techniques to the local needs of those farmers.
- Small-scale farmers may not have taken a leading role in developing the technology, but they were important participants in the process.

- The information was presented in a way that enabled small-scale farmers to assimilate it. For instance, the dissemination program in Ghana established accessible demonstration plots that were large enough to show farmers the advantages of no-till under farmers' conditions (at least 1,000 m^2 for the farmers' "standard practice" plot and for the no-till plot). The size was also convenient for calibrating the 15-liter sprayer (Findlay and Hutchinson 1999). The demonstration program included pre-season farmer training, on-farm demonstrations, field days, field tours, workshops and seminars, and distribution of fact sheets and production guides.
- Since small-scale farmers lack resources to travel, a large network of demonstration plots must be established. Farmers should not have to travel more than 50 km to attend field days.
- Farmer-to-farmer communication is a crucial instrument in convincing small-scale farmers that they can adopt the technology even with their limited resources.

Although agrochemical companies realized that no-till could open important markets for their products and were willing to invest in developing the appropriate technological packages, their participation was not a determining factor in the success of the technology. For example, Monsanto invested in developing no-till packages for small-scale farmers in many countries on three continents with limited success.

Despite the common belief that farmers are reluctant to accept change, no-till experiences in several countries show that both large- and small-scale farmers adopt new technologies very fast when the benefits are clear and the package fits their needs and constraints. A slow rate of adoption indicates deficiencies (either technical or economic) in the package. More than three decades of research on no-till have yielded a wealth of technical information; the key issue faced by no-till networks in nonirrigated areas is how to use the available information to develop a locally appropriate package. When the right network emerges, research and adoption proceed quickly: development of the first packages in South America took about two decades, but in Ghana it took about five years.