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## **Conservation Agriculture in Maize- and Wheat-Based Systems in the (Sub)tropics: Lessons from Adaptation Initiatives in South Asia, Mexico, and Southern Africa**

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*Conservation agriculture's underlying principles—minimal soil disturbance, soil cover and crop rotation—are increasingly recognized as essential for sustainable agriculture. This article summarizes three contrasting cases of adapting conservation agriculture (CA) to smallholder conditions in the (sub)tropics: a) irrigated rice-wheat systems in South Asia; b) rainfed maize/wheat and irrigated wheat systems in Mexico; and c) rainfed maize in Southern Africa. In the South Asia case, farm surveys show rapid and widespread adoption of zero tillage wheat—primarily due to a substantial cost saving (15–16%). In the other cases, uptake so far has been limited—although long-term trials show continuously higher and more stable yields both for maize and wheat. Under marginal conditions CA can generate substantial yield increases—averaging some 50% over conventional smallholder maize yields of 1 ton per ha over 6 years in on-farm trials in Southern Africa. The diverse*

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*experiences attest to the wide adaptability of CA systems, which can generate clear economic and potentially enormous environmental benefits. The case studies and wider literature however also reiterate the substantial challenges in terms of targeting, adapting and adopting CA—particularly for smallholders in the (sub)tropics. CA systems are best developed in situ through a multi-stakeholder adaptive learning process to create viable CA-based options that are technically sound, economically attractive, and socially acceptable.*

*KEYWORDS* adaptation; cereal systems, conservation agriculture, innovation systems, smallholders

Conservation agriculture (CA) is increasingly advocated as essential for soil health and sustainable agriculture (Food and Agriculture Organization 2007; Harrington and Erenstein 2005; Hobbs 2007; Hobbs et al. 2008). CA revolves around three core principles: minimal soil disturbance, retention of soil cover, and a rational use of crop rotations. The original interest in CA related to its potential to conserve soil and water and enhance soil health (e.g., by reducing soil organic matter decline, soil structural breakdown, and soil erosion). However, CA systems potentially also save energy (e.g., tractor fuel, animal tillage, human labor), lead to more efficient use of water and other inputs and reduce production costs. CA has, thus, become increasingly relevant, particularly the reduction in fuel associated with minimal tillage in view of surging fossil fuel prices and global warming concerns.

Minimal soil disturbance long posed particular challenges to the adaptation and uptake of CA. This typically implies that a crop is established without any or with minimum prior tillage, a practice variously known as no till(age), zero-tillage, direct seeding, conservation tillage, and reduced tillage. The crop establishment can take various forms depending on mechanization levels, and includes tractor or animal drawn direct seeders and manual planters (e.g., jab-planter). Despite the popularity of some of the other designations for minimal soil disturbance, the array of names and varying interpretation can be confusing and tends to put too much emphasis on the tillage component and thereby tends to ignore the other CA principles. Indeed, minimal soil disturbance alone is an insufficient condition for CA. Competing crop residue uses and residue management practices impose significant challenges for the retention of soil cover across the (sub)tropics (Erenstein 2002, 2003; Wall 2009). The distinction between CA and the tillage-based designations is important because the minimal soil disturbance alone, while attractive in the near term, may be unsustainable in the longer term (Harrington and Erenstein 2005). For instance, the use of minimal soil disturbance without residue retention and without suitable rotations, under

some circumstances, can be more harmful to agroecosystem productivity and resource quality than a continuation of conventional practices (Wall 1999; Govaerts et al. 2005).

The adaptation and uptake of CA has so far been more successful for larger scale agriculture in relatively temperate environments—be it in Brazil, Argentina, the United States, or Australia (Derpsch and Friedrich 2009; Kassam et al. 2009). More challenging has been the adaptation of CA to the conditions of resource poor farmers—hereafter referred to as smallholders irrespective of tenancy status—and tropical environments (e.g., Knowler et al. 2003; International Institute of Rural Reconstruction & African Conservation Tillage Network 2005; Bolliger et al. 2006; Friedrich and Kassam 2009; Giller et al. 2009).

A major drawback for CA adaptation and its uptake is its relative complexity. Although the CA principles are defined as common to CA systems—the actual implications can vary substantially across agroecosystems and farmers. As highlighted by Harrington and Erenstein (2005), “the specific components of a conservation agriculture system (establishment methods, farm implement selection, crops in the rotation, soil fertility management, crop residue and mulch management, germplasm selection, etc.) tend to be different across environments. Local investments in adaptive research are typically needed to tailor conservation agriculture principles to local conditions” (32–33). This adaptation of CA-based component technologies is essential so as to create viable options—that is, options that are technically sound, economically attractive, and socially acceptable. A recent review indeed called for CA promotional efforts to be tailored to reflect the particular conditions of individual locales (Knowler and Bradshaw 2007).

The CA adaptation process is most efficient when a local “innovation system” emerges and begins to acquire a self-sustaining dynamic (Harrington and Erenstein 2005). When this happens, “. . . technology development and adoption [become a] social phenomenon 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 that they create.” (Ekboir 2002, 2). Innovations systems have emerged around CA practices across a range of emerging economies—in South and Meso America (e.g., Brazil, Bolivia, Paraguay, Mexico), Africa (e.g., Ghana, southern Africa), and Asia (the Indo-Gangetic Plains of South Asia, China and Central Asia; Ekboir 2002; Harrington and Erenstein 2005). Success in the development and dissemination of CA practices for smallholders requires targeting areas with specific economic opportunities for CA and an integrated approach with a practical orientation, farmer participation, community involvement, flexibility, and a long-term perspective (Erenstein 2003; Hellin 2006). Indeed, even a recent review

of the Brazil case which is widely perceived as the CA's longest success story, still saw the need for more holistic, participatory and adaptive on farm-research (Bolliger et al. 2006).

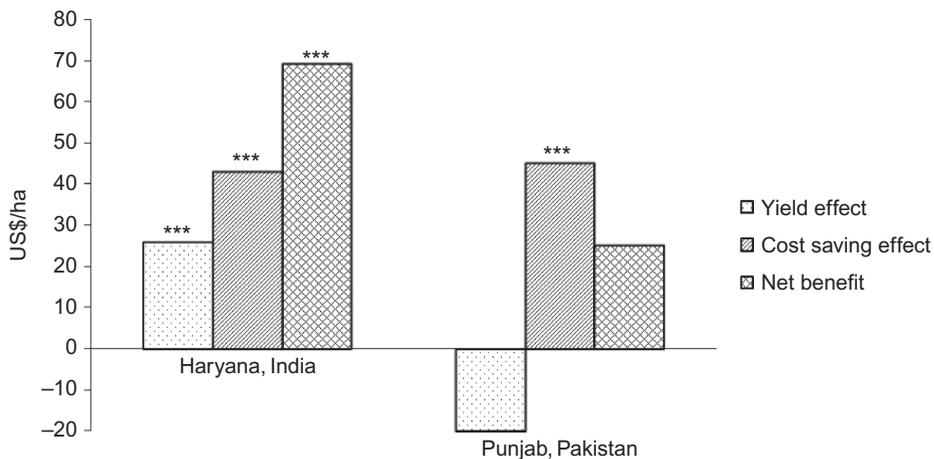
The International Maize and Wheat Improvement Centre (CIMMYT, [www.cimmyt.org](http://www.cimmyt.org)) is actively engaged in adapting CA to smallholder maize (*Zea mays* L) and wheat (*Triticum* spp. L) systems in the tropics and subtropics, with agronomic work dating back to as early as the 1980s (e.g., Barreto et al. 1989). CIMMYT's long experience with CA is particularly relevant for two reasons. First, maize and wheat are two of the world's three most important cereals. Adapting CA to maize and wheat systems implies a major impact that cuts across continents and emerging economies. Second, CIMMYT has long been a strong advocate of on-farm research and has actively worked with farmers, national agricultural research and extension systems (NARES), and other partners to adapt CA practices to local smallholder conditions in both irrigated and rainfed and both wheat and maize systems.

The purpose of this article is to summarize and draw lessons from some of CIMMYT's experiences with the adaptation of CA to smallholders' conditions in the (sub)tropics. We thereby focus on three contrasting cases of ongoing CA research and development (R&D) in emerging economies: (i) irrigated rice-wheat systems in South Asia; (ii) rainfed maize/wheat and irrigated wheat systems in Mexico; and (iii) rainfed maize in Southern Africa.<sup>1</sup> A common thread through these cases are the need for research for development partnerships with NARES, agri-business, farmers, and other stakeholders with an ultimate vision of sustainable smallholder wheat and maize systems based on the principles of CA. After the case studies, the article continues with a broader discussion on CA innovation systems and impact pathways and CA adoption, prior to concluding.

## CASE 1: IRRIGATED RICE-WHEAT SYSTEMS IN SOUTH ASIA

The Green Revolution transformed the Indo-Gangetic Plains (IGP)—spreading from Pakistan, through northern India and the Nepal terai region to Bangladesh—into the cereal basket of South Asia, with rice-wheat systems now covering an estimated 14 million ha in the region. The technological packaging of improved wheat and rice seed, chemical fertilizer, and irrigation in an overall supportive environment for agricultural transformation led to rapid productivity growth. Over the past decade productivity growth has, however, stagnated, leading to concerns over national food security and lagging rural economic growth. The degradation of the natural resource base is widely seen as the root cause for the recent stagnation. CA-based resource conserving technologies are increasingly perceived by the R&D community as the means to reverse land degradation and restore productivity growth (Erenstein, Farooq, et al. 2008; Erenstein and Farooq 2009).

To date, most significant progress has been made with addressing the challenge of reducing soil disturbance for establishing wheat in the rice-wheat systems of the IGP. Land preparation in these systems relies on tractors with intensive tillage for each crop. The prevailing zero tillage (ZT) practice relies on a mechanical tractor mounted seed drill with 6–13 inverted T-openers that can place wheat seed and fertilizer in shallow narrow slits in untilled rice fields. The ZT drills can, thereby, drastically reduce tillage intensity for the wheat crop from eight to a single tractor pass. Farm household surveys in 2003–2004 confirmed significant adoption of ZT wheat in the rice-wheat systems of NW IGP: 34.5% in India's Haryana and 19% in Pakistan's Punjab (Erenstein 2010). Experts estimate the combined ZT and reduced tillage (ZT + RT) wheat area in the IGP to amount to some 2 million ha in 2004–2005 ([www.rwc.cgiar.org](http://www.rwc.cgiar.org)). The main driver behind the rapid spread of ZT wheat is the significant, immediate and recurring “cost saving effect,” which makes adoption profitable (Figure 1, corresponding with a 15–16% saving on operational costs; Erenstein, Farooq, et al. 2008a). The cost saving effect primarily reflects the drastic reduction in tractor time and fuel for land preparation and wheat establishment. A significant “yield effect” can further boost the returns to ZT (Haryana, India, in Figure 1, corresponding with a 4% yield increase over average farmer reported conventional yields of 4.2 tons per ha; Erenstein, Farooq, et al. 2008). The yield effect, if any, is closely associated with enhanced timeliness of wheat establishment after rice. Terminal heat implies that wheat yield potential reduces by 1–1.5% per day if planting occurs after mid November. Late wheat sowing is a widespread problem in the Indian IGP, and ZT allows for timelier establishment.



**FIGURE 1** Financial advantage of zero tillage over conventional tillage for wheat in adopter farms in 2003–2004 in Haryana, India and Punjab, Pakistan (farmer survey findings; columns with superscript\*\*\* differ significantly from zero ( $t$  test 0.01) *Source:* Adapted from Erenstein, Sayre, et al. 2008; Erenstein 2009).

Smallholders prevail in the IGP—with an average farm size in India of 3 ha in the NW IGP and less than 1 ha in the eastern plains (Erenstein and Thorpe 2010). ZT adoption so far is closely associated with the farm resource base and rice-wheat specialization (Erenstein and Farooq 2009). The significant wheat area of ZT adopters implies larger annual benefits, lower relative learning costs and earlier payback to a ZT drill investment—but also raises some equity concerns. The structural differences between ZT adopters and non-adopters also potentially confound the assessment of ZT in farmers' fields (Erenstein 2009).

The reduction of tillage for wheat had limited negative spillovers on weed management practices, in part associated with the limited turnaround and untilled rice fields being relatively weed free. In fact, by reducing soil movement ZT proved to be an effective control measure of *Phalaris minor*—a problematic weed that showed emerging resistance to the widely used isoproturon herbicide (Erenstein and Laxmi 2008). Survey results also show that the use of ZT in wheat had limited spillovers on the productivity and management of the subsequent rice crop (Erenstein, Farooq, et al. 2008). For the rice crop in the IGP, intensive and wetland preparation followed by transplanting still prevails. The reduction of tillage in rice-wheat systems has thus only been partially successful reflecting the increasing acceptance of ZT for wheat, with the challenge of reducing soil disturbance for rice still remaining.

The success of reducing tillage for wheat had much to do with the adequate development of local and adapted delivery pathways of ZT drills. Several factors proved crucial to its success in India (Erenstein and Laxmi 2008; Seth et al. 2003). A local manufacturing capacity was developed to produce and adapt ZT drills at a competitive cost. The private sector could see substantial market opportunities for their products, whereas the involvement of several manufacturers ensured competitive prices, good quality, easy access to drills by farmers, along with guaranteed repairs and servicing. Close linkages of scientists and farmers with the private manufacturers including placement of machines in villages for farmer experimentation allowed rapid feedback and refinement of implements. Private ZT service providers have made the lumpy technology divisible. Recent adoption surveys revealed that 60–74% of ZT adopters did not own a ZT drill (Erenstein 2010). Service providers have the added advantage of having hands on experience and having the self-interest in promoting the technology. Strong support from state and local government officials helped with dissemination, including the provision of a subsidy to lower the investment cost and laying out extensive on-farm demonstrations and trials. The direct exposure of farmers to ZT in their own environment proved critical in overcoming widespread initial disbelief about the viability of establishing a wheat crop without the traditionally intensive tillage. The Rice Wheat Consortium (RWC) for the Indo-Gangetic Plains ([www.rwc.cgiar.org](http://www.rwc.cgiar.org), hosted by CIMMYT during

1999–2007) played a crucial catalytic role in promoting the public–private partnership, nurtured it through its formative stages and facilitated technology transfer from international and national sources (Seth et al. 2003). It has been estimated that the investments made by RWC and CIMMYT accelerated adoption of ZT/RT by five years and yielded significant economic benefits (Erenstein and Laxmi 2010).

The adoption of ZT/RT in the IGP is still primarily concentrated in the NW IGP (Erenstein 2010)—which corresponds with the more intensive and productive rice-wheat systems and more favorable institutional support. Extending ZT/RT to the eastern IGP presents additional challenges, including the marked rural poverty and less favorable institutional context. Most of the ZT/RT relies on the tractor drawn ZT drill, but in pockets—particularly low lying areas in the Eastern plains—there is also adoption of surface seeding into the previous crop. The increased use of ZT in wheat also serves as a potential stepping stone to permanent beds in irrigated wheat systems.

In spite of the success of the RWC with adapting and promoting ZT/RT practices for wheat in irrigated agriculture in the IGP, the full environmental benefits offered by CA are yet to be fully realized (Gupta and Sayre 2007; Erenstein and Laxmi 2008). The vast majority of farmers in the IGP have adopted ZT/RT for wheat because it provided immediate, identifiable and demonstrable economic benefits such as reductions in production costs, savings in fuel and labor requirements, and timely establishment of crops resulting in improved crop yields. But, in spite of the clear benefits and increasing adoption of ZT/RT, most farmers, especially the small and medium scale farmers, have difficulties in following the wider basic tenets of CA, particularly year-round minimal soil disturbance, residue retention, and crop rotation. Most farmers do not retain crop residues on the soil surface as they use crop residues for other purposes, particularly to feed livestock and burn surplus rice residues (Erenstein and Thorpe 2010). The ZT/RT wheat as currently applied in the rice-wheat systems of the IGP, thereby, has three distinctive features that distinguish it from related systems elsewhere: ZT/RT being applied to only one crop in a double cropped system; not necessarily increasing herbicide use; and not necessarily retaining crop residues as mulch (Erenstein and Laxmi 2008). Therefore, building on the success of ZT/RT wheat, R&D still faces the challenge of adapting and developing sound, economic CA practices that farmers will adopt year round and across crops in the system.

## CASE 2: RAINFED MAIZE/WHEAT AND IRRIGATED WHEAT SYSTEMS IN MEXICO

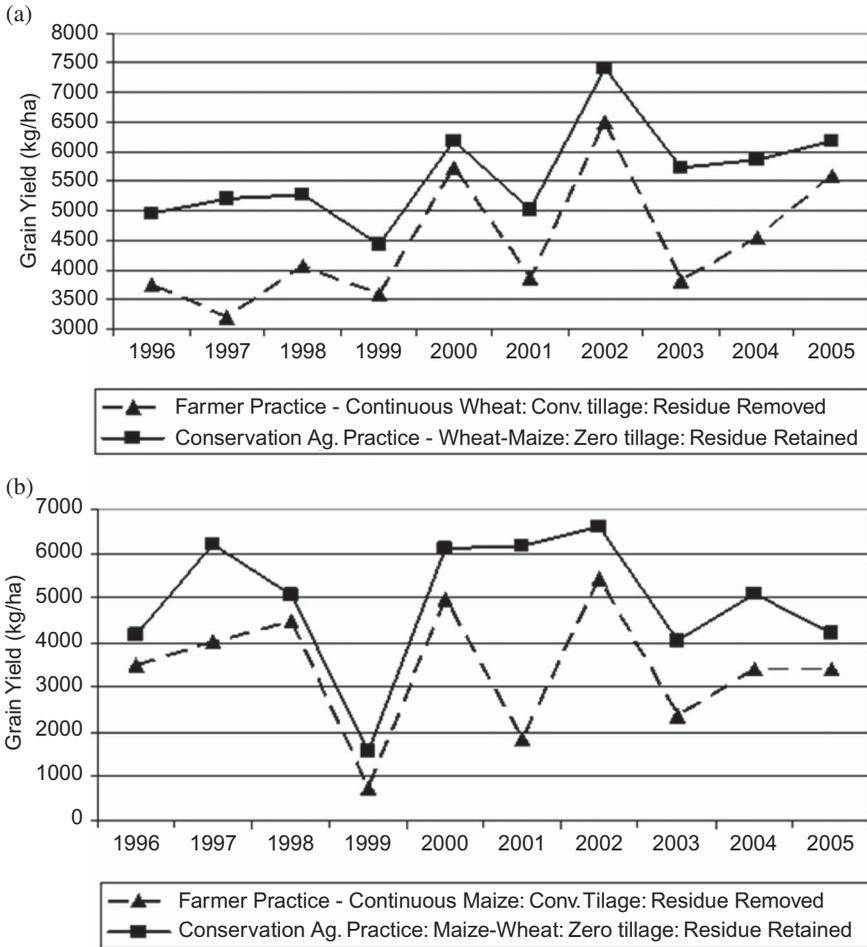
CIMMYT manages a series of long-term trials in Mexico. One such rainfed trial is located in the central highlands—an area characterized by

predominantly rainfed cropping by smallholders with annual rainfall averaging between 350 and 800 mm, occurring during a 4–6 month summer wet season followed by dry and frosty winters. Farmers plant crops, dominated by maize, at or just before the onset of the main, summer rains. Most rain events are intense, afternoon storms and there can be significant dry spells with crop water stress at any time during the cropping season. In farmers' fields, the soil is bare for much of the year since almost all crop residues are directly removed for fodder or are pastured or burned. Farmers subject their fields to frequent tillage and the heavy tillage and lack of ground cover on sloping fields lead to extensive erosion and water runoff, resulting in the loss of precious water (Govaerts et al. 2005).

The rainfed long-term trial was established in 1991 at El Batan (CIMMYT headquarters) to investigate the long-term effects of different tillage, crop residue management practices, and crop rotations (Fischer et al. 2002a, 2002b). The trial includes treatments based on the CA tenets, including establishment with tractor mounted ZT drills (a disc coultter for wheat and a double disc opener for maize), residue retention and crop rotation and using appropriate herbicides as needed. The trial also includes the most common smallholder practices for maize and wheat production in the surrounding rainfed region—that is, intensive tillage (by tractor-drawn disc ploughs and harrows and field cultivators), residue removal and continuous cropping of the same crop.

Results from the long-term trial confirm the potential benefits of CA for farmers in the rainfed highlands of Mexico (Govaerts et al. 2005; Govaerts, Mezzalama, et al. 2006; Govaerts, Sayre, et al. 2006; Govaerts, Fuentes, et al. 2007; Govaerts, Mezzalama, et al. 2007). The grain yields for wheat and maize over a 10-year period (1996–2006) are presented in Figure 2. It illustrates that the best CA practice (ZT, retention of crop residues, and rotation of maize and wheat) provided continuously higher and more stable yields for both wheat and maize compared to the farmer tillage and residue removal practice, even though optimum inputs and cultivars were used in all cases. The current tillage-based practices combined with crop residue removal on already degraded soils, imply that farmers continue to degrade the productive capacity of their land further. This also implies they undermine their ability to capture the potential returns to new improved cultivars. Similarly, with the current traditional wheat and maize cropping practices, other inputs will not be efficiently utilized, including, in particular in this case, rainfall. The long-term trial also highlights that CA practices are economically viable and attractive. On average, the value of the yield gain and cost savings provides substantial returns over variable costs for both wheat and maize, against losses for the farmers' practice. The reduced yield risk in rainfed systems is another significant benefit for smallholders.

CIMMYT also conducts similar long-term trials in the irrigated, areas in northwest Mexico. The main focus has been in the Yaqui Valley located in



**FIGURE 2** Comparison of rainfed yields for (a) wheat (LSD(0.05) 800 kg/ha) and (b) maize (LSD(0.05) 796 kg/ha) for the most common farmer practice versus the best CA practice at El Batán, central Mexico 1996–2005 (*Source*: CIMMYT CA trials in Mexico; adapted from Erenstein, Sayre, et al. 2008).

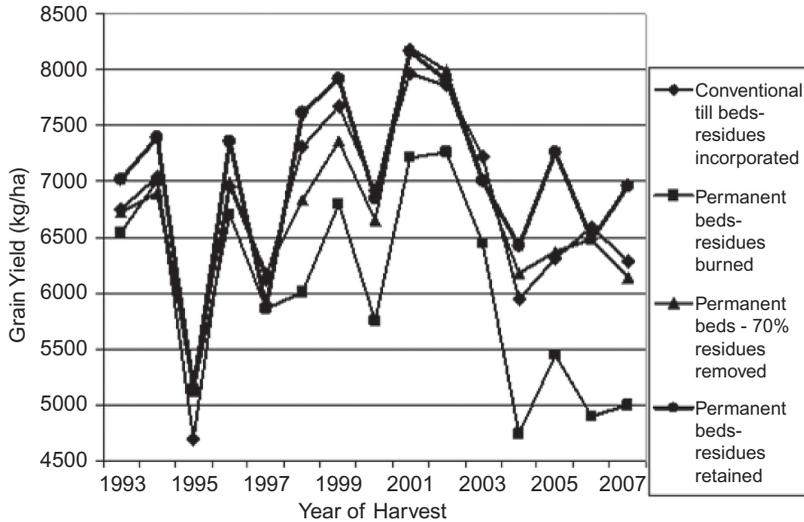
the state of Sonora. This valley encompasses about 255,000 ha of irrigated land using primarily gravity irrigation systems fed from canals (over 80% of irrigation water) and deep tube wells (around 20% of irrigation water). Farming is mechanized but operational farm size can range from less than 10 ha to several hundred hectares or more. In the past farmers planted all their crops on the flat with basin/flood irrigation, but over the past 25 years more than 95% of the farmers—including smallholders—have changed to planting all crops, including wheat, the most widely grown crop, on raised beds spaced at 70–100 cm, bed center to bed center (Aquino 1998). Irrigation water is applied in the furrows between the beds.

Wheat yields for the Yaqui Valley have averaged over 6 t/ha over the past several years. Farmers growing wheat on beds obtain about 8% higher yields with nearly 25% less operational costs and irrigation water use as compared to those still planting conventionally on the flat, using border/basin flood irrigation (Aquino 1998). Most farmers, however, currently still practice conventional tillage by which the beds are destroyed after the harvest of each crop by several tillage operations before new beds are formed for planting the succeeding crop. This tillage is often accompanied by burning of the crop residues although some maize and wheat straw is baled-off for fodder and, when turnaround-time permits, some crop residues are incorporated during tillage (Meisner et al. 1992).

There has been intense farmer interest in the development of new production technologies based on CA principles (Govaerts et al. 2009). These would allow marked tillage reductions which, when combined with retention of crop residues, have the potential to reduce production costs, improve input-use efficiency, permit more rapid turnaround between crops and more sustainable soil management while still allowing the use of the relatively inexpensive gravity irrigation system. Therefore, a long-term experiment was initiated in 1992 in the Yaqui Valley to compare the common farmer practice, based on extensive tillage to destroy the existing beds with the formation of new beds for each succeeding crop with the permanent raised-bed system where new beds are formed after a final tillage cycle and are then reused as permanent beds with only superficial reshaping as needed before planting of each succeeding crop.

Figure 3 presents the wheat yield trends observed from the long-term trial for four contrasting tillage and residue management practices from 1993 to 2007. In the rainfed production systems in central Mexico, CA practices—ZT with proper residue management—provided almost immediate benefits in grain yields (Figure 2) due mainly to more efficient rainwater use. In contrast, under the irrigated conditions in the Yaqui Valley no major wheat yield differences were observed between the various contrasting tillage and residue management practices for the first five years—10 crops including the soybean or maize crops planted each summer in rotation with wheat (Figure 3). However, wheat yield declined radically from the 1998 crop onward on the permanent raised-bed treatment where all crop residues from both summer and winter crops were burned. The wheat yield of this practice has been continually and dramatically below the other management practices ever since.

There are many examples where farmers using ZT planting without retention of adequate surface residues under rainfed production conditions have failed to achieve satisfactory results. However, there has been little work on adapting CA to gravity-irrigated conditions and so there are few clear examples of the need for surface residue retention. The results shown in Figure 3, therefore, clearly reinforce the need for adequate retention

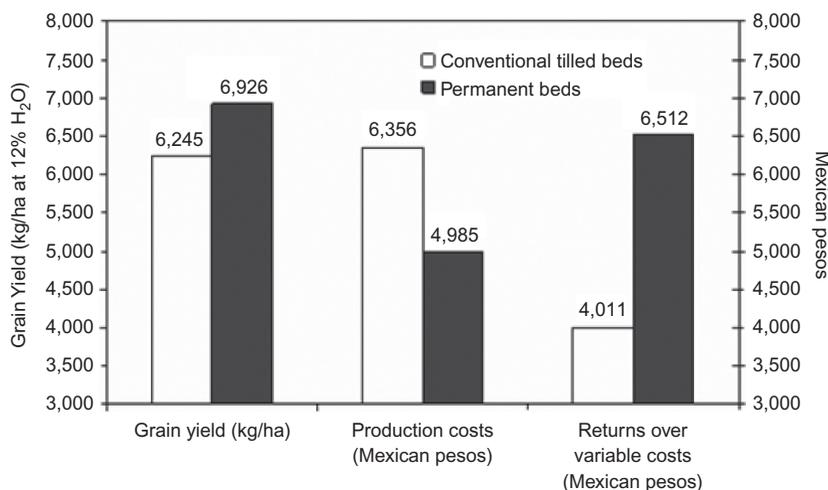


**FIGURE 3** Effect of tillage and residue management on wheat grain yields with optimum management in the Yaqui Valley, Sonora, Mexico 1993–2007 (LSD(0.05) 371 kg/ha. (Source: CIMMYT CA trials in Mexico; Adapted from Erenstein, Sayre, et al. 2008).

of surface residues in attaining sustainable, long term ZT systems and demonstrate the need to maintain a long-term perspective for CA activities.

Figure 4 illustrates the clear yield and economic advantage of permanent raised beds over conventionally tilled beds. These results are derived from a large-scale trial or farmer demonstration module where crops are planted when possible for each planting system (usually 7–10 days earlier for wheat in the permanent beds as compared to tilled beds due to faster turnaround times between crops). In the trial reported in Figure 3, the planting date each year has been the same on all treatments. Because of the marked economic advantages of the permanent raised-bed planting systems, farmers in the Yaqui Valley are now in the early stages of adopting the system. An initial constraint to its spread was the lack of appropriate seeders but multi-crop multi-use implements have been adapted and are now commercially available in the area (Govaerts et al. 2009).

Despite the potential economic benefits, adoption of CA practices in both rainfed and irrigated systems in Mexico has so far been limited. The Mexican NARES have been variously involved in CA research and promotion in a number of states since the 1990s (Erenstein 1999). This has resulted in some examples of CA adoption, but widespread adoption of CA in Mexico has not occurred (Erenstein 1999). In some instances, small and medium-scale farmers may not have access to the means to adopt appropriate CA technologies. For instance, one study in western Mexico concluded that although ZT was economically viable, cash-constrained small-scale farmers,



**FIGURE 4** Comparison of average wheat grain yields (LSD(0.05) 407 kg/ha), variable production costs and returns over variable costs of wheat produced with conventional tilled beds versus permanent raised beds in the Yaqui Valley, Sonora, Mexico 2001–2004 (*Source*: CIMMYT CA trials in Mexico; adapted from Erenstein, Sayre, et al. 2008).

especially in the dry areas, may not readily adopt it because they lack seeding equipment and need techniques that are less reliant on herbicides (Jourdain et al. 2001). Other studies show that the short-term returns to CA adoption in rainfed systems in Mexico can be constrained by relatively modest immediate benefits and substantial transition costs, including adaptations to crop production, the farm enterprise, and the institutional setting (Erenstein 1999). Crop residue retention as mulch can, thereby, be constrained by the prevalence of stubble grazing during the dry season or the burning of surplus residues during land preparation. This calls for more participatory and adaptive research in farmers' fields and rural communities to adapt CA to their circumstances. It also flags the need to use long-term trials to highlight the cumulative and substantial benefits over time to farmers and other stakeholders.

### CASE 3: RAINFED MAIZE SYSTEMS IN SOUTHERN AFRICA

Drawing on experiences with CA elsewhere, CIMMYT began a concerted effort in 2004 to adapt the CA principles to the circumstances of smallholders in southern Africa (Malawi, Tanzania, Zambia, Zimbabwe, and, more recently, Mozambique). Maize is the staple food of the vast majority of the population of southern Africa and accounts for 50–90% of caloric intake, with greatest dependence on maize for food among the very poor. It is, therefore, the main crop grown by the majority of smallholders who

generally focus their production strategies on fulfilling family food requirements and then selling any excess production for cash. CA systems have been developed and used on large-scale commercial farms in South Africa and Zimbabwe, but until recently there has been little emphasis on extending these practices to smallholders. However, currently there is much interest in CA in many countries of the region, and major efforts are underway in Zambia (Haggblade and Tembo 2003) and Zimbabwe to spread a particular type of CA, locally called Conservation Farming, based on planting in small, manually dug basins.

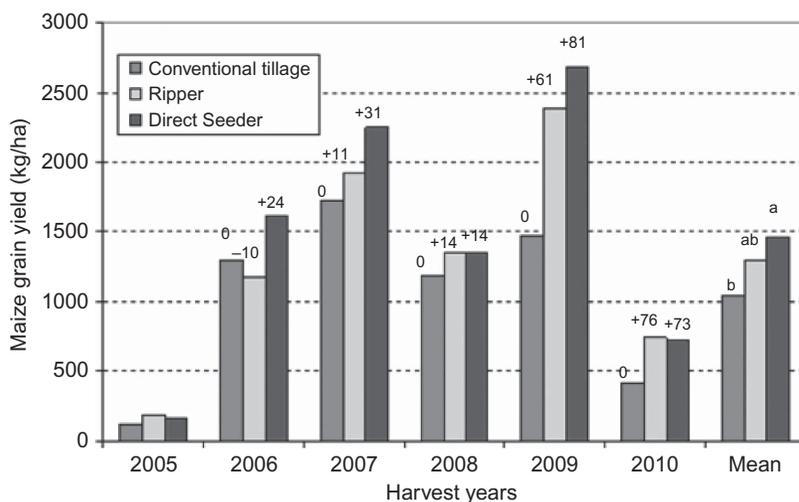
One of the major lessons learned from other regions of the world is the importance of knowledge in the development and spread of CA, not only among farmers but also among researchers, extension agents and others involved in agricultural development. The principles of CA have widespread applicability, but the techniques and technologies necessary to put those principles into practice vary widely from place to place and with different socioeconomic conditions: Farmers (and others) need to understand the principles of CA, and why they work, to be able to successfully modify and adapt CA options to their own particular conditions. Therefore, CIMMYT's activities to help spread CA in southern Africa focus on a limited number of communities, with relatively intensive participatory research, demonstration, and learning activities in these communities.

There are a number of constraints that potentially affect smallholder adoption and interest in CA (Wall 2007). There can, thus, be many impediments to the widespread adoption of CA, but concerted effort to achieve sustainable systems is urgently needed—especially as efforts dedicated to nonsustainable systems not only waste resources but also undermine development in the medium to long term. Competition for crop residues is a major concern for developing CA systems for smallholders in rainfed areas (Erenstein 2003; Wall 2009). Many therefore say that CA is impossible under these conditions because of the need to use crop residues for animal feed. However, the alternative of an ever-declining resource base is not an acceptable option—there is a need to invest heavily in finding appropriate techniques to make CA viable and thereby convincing farmers, researchers, extension agents, and politicians that there are alternatives to the doomsday practices of conventional agriculture. Experiences so far show that farmers are prepared to leave crop residues on their fields with evident benefits and farmer experimentation on their own production fields has begun (Wall 2009).

On-farm demonstration plots comparing CA options with conventional smallholder land preparation were initiated in central and north-east Zimbabwe in 2004 (Wall and Thierfelder 2009). In central Zimbabwe the work focused on the Zimuto Communal Area near Masvingo, where conditions are particularly harsh, with infertile sandy soils (93% sand), low and erratic rainfall (200–1000 mm yr<sup>-1</sup>, mean 631 mm), and the risk of

crop failure is high. A series of smallholder-managed demonstration plots comparing the farmers' conventional animal traction tillage practices with two CA systems have been conducted on the same sites each season. The first of the CA practices is a low-outlay intermediate option where the farmer replaces the moldboard ploughshare with a ripper tine on the same frame and uses this to open narrow furrows, normally 75–90 cm apart, and seed by hand into these furrows. The second is a more expensive option using an imported animal traction direct seeder—although local production of adapted equipment is being stimulated, as yet the prototypes are still undergoing participatory evaluation. Over six years average yields with the animal traction direct seeder were significantly and substantially higher (some 50%) compared to the conventional farmer practice (average 1 ton per ha)—with intermediate yields for the ripper (Figure 5). However, there were substantial annual rainfall and yield fluctuations—for example, the initial 2004–2005 season was very dry with marginal yields for all treatments, whereas 2005–2006 season was very wet and the 2006–2007 season more normal—approximately 600 mm of rain but with extended dry periods. Further, in most of the individual years the yield effect was not significant (e.g., Wall and Thierfelder 2009)—albeit that the direct seeder tended to consistently compare favorably to the conventional farmer practice.

In northeast Zimbabwe, the work focused on smallholder-managed plots around Chavakadze village near Shamva. Conditions for maize are more favorable with heavier soils ranging from sandy loams to clay soils



**FIGURE 5** Mean grain yield of maize for different tillage treatments in on-farm demonstration plots in central Zimbabwe, 2005–2010 (overall mean treatment columns with different superscript letters differ significantly (0.05) (*Source*: CIMMYT CA project in Southern Africa; unpublished data) (color figure available online).

and with higher precipitation (average approximately 800 mm yr<sup>-1</sup>). The trials compared the same tillage treatments as in central Zimbabwe, albeit in a maize-soybean rotation and with glyphosate applied to half of the two CA treatments at seeding—all other weed control in these plots and in the farmers' check done manually (Wall and Thierfelder 2009). Still, results have been relatively similar, with the direct seeding comparing favorably to the conventional farmer practice but yield differences not being statistically significant (e.g., Wall and Thierfelder 2009). The relative lack of statistically significant differences between treatments is in part associated with the variability inherent to on-farm work and the limited number of on-farm trials (6–7 per site). On-station trials in Zambia and Zimbabwe confirm that CA improves the crop water balance, albeit that these do not always result in higher crop yields unless there is marked moisture stress during the season (Thierfelder and Wall 2010; Wall and Thierfelder 2009).

In the southern Africa context, the economic benefits of CA are still difficult to quantify unambiguously and are confounded by location specificity and seasonal variability, and the corresponding risk implications. However, for smallholder farmers, cash benefits per unit of land may not be the most important measure: labor productivity (Ekboir et al. 2002) and risk reduction are likely more important factors. Labor savings with CA are very evident where chemical weed control has been used (e.g., in Ghana [Ekboir et al. 2002] and our experience in Malawi) but are not as evident (and may even be negative in the first years) when manual weeding is done, leading to many cases of disadoption (Rockstrom et al. 2003). Manual hoe weeding also implies considerable soil movement and thereby reduces the benefits of CA.

Social issues can also be problematic for many smallholders in the (sub)tropics—often relying on rainfed mixed crop-livestock systems where communal stubble grazing after the harvest is the norm (Wall 2009). Once the harvest period is over, grazing animals are free to roam and an individual farmer is unable to protect his or her residues. Overcoming this social issue involves community participation: it is important that the whole community realizes the benefits of CA and the long-term deleterious effects of soil organic matter decline. The ongoing on-farm work illustrates it is possible to overcome this issue. For instance in northern Tanzania a collaborating farmer convinced his neighbors of the benefits of CA and that the community should restrict the free grazing of their animals. In northeastern Zimbabwe a local policymaker observed the benefits of residue retention in the CA demonstration and validation plots and has re-enacted local and forgotten regulations which permit farmers to deny access to their fields to grazing animals. This latter example shows the benefits not only of the CA demonstration to farmers, but also of the incorporation of policymakers into the innovation system.

Spreading the use of CA is not so much about technology, but about mind-set and the way people think. For instance, the word for agriculture

and ploughing is the same in the Shona language. People need to learn to dissociate the two concepts: agriculture does not depend on ploughing, and continuing to plough tropical soils, with the resultant soil organic matter decline, structural degradation and soil erosion, is unsustainable.

Spreading CA under smallholder conditions will not be easy and, as has been the case elsewhere, it takes considerable time (at least 10 years) to achieve appreciable levels of CA adoption—but once the pioneers have mastered the system, adaptation and adoption can become rapid. However, continuity and persistence are necessary—not only on the part of farmers and agricultural workers, but also on the part of governments and aid agencies.

### CA INNOVATION SYSTEMS AND IMPACT PATHWAYS

Of the wide range of smallholder farming systems around the world (Dixon et al. 2001), the cases reported in this article focus on maize and wheat systems in contrasting settings in the (sub)tropics (Table 1). The diverse series of CIMMYT experiences with CA practices are testament to the wide adaptability of CA systems. The cases comprise two intensive irrigated wheat-based systems and two rainfed maize systems. The level of production risk in the rainfed systems is naturally higher, but the cases show how CA practices can enhance yields in the short-term and reduce yield variability—particularly

**TABLE 1** Selected characteristics of the case studies

	Case 1	Case 2a	Case 2b	Case 3
Location	South Asia (NW India, Pakistan)	Mexico (central)	Mexico (NW)	Southern Africa (Zimbabwe)
Cropping system	Irrigated rice-wheat	Rainfed maize/wheat based	Irrigated wheat based	Rainfed maize based
Yield variability	Low	High	Low	Very high
Yield effect CA practices	Positive due to timely planting	Already positive in short-term and more stable	Positive but with 5 year delay	Already positive in short-term and more stable
Local innovation systems capacity	Medium, with active collaborative equipment innovation	Low innovation	High level of innovation	Generally low
Residue management	Wheat straw used for livestock feed; rice straw surplus burned	Used for livestock feed	Surplus burned and/or incorporated	Used for livestock feed
Adoption CA practices	Rapid for ZT wheat in the NW IGP	Low	Low	Negligible

through water conservation. The accounts illustrate the clear economic benefits which accrue to farmers and society from adopting elements of CA in irrigated systems in South Asia and Mexico, and the potential benefits of CA in rainfed systems in Southern Africa and Mexico. However, as shown in the irrigated long term trials in Mexico, the benefits might not be apparent during the first (5) years; hence, the importance of a long-term vision in agricultural research and the value of long term trials. It also illustrates the challenge of making CA more attractive to smallholders whose time horizons often by necessity are short term as opposed to medium or long term.

The foregoing cases also illustrate the merits of approaching CA R&D as a multi-stakeholder innovation system, as indicated in the introductory sections of this article. Each case shows the importance of engaging multiple stakeholders (farmers, researchers, business, machinery manufacturers, marketing agents, etc.) in the development and adaptation of the CA systems and the supporting agricultural institutions. Of course, development of CA systems is not a one-off input: The systems must be capable of dynamic responses to changing circumstances. CA requires the coordinated application of a series of new crop management practices which need adaptation to local conditions. The lack of adapted equipment for CA is often a binding constraint, which can be overcome through the close involvement of machinery manufacturers. Similarly, the engagement of input suppliers and access to markets has been an essential ingredient of successful adaptation and adoption of CA.

Another critical issue for environmental sustainability is the management of crop residues, which varies depending on biomass production, equipment, and alternative demands for crop residues for energy or livestock. It is clear that a considerable period of adaptation was, or will be, required before a significant number of farmers adopt. For instance, the southern Africa case is just getting under way and so significant adoption could not be expected before 5–10 years.

One challenge that CIMMYT and other organizations face is better diagnosis of the constraints to faster development and adoption of CA practices, and estimating the complex and far-reaching impacts of CA research (Dixon et al. 2007). With such information CIMMYT is better placed to work with partners to ensure that CA practices are more widely adopted or adapted and contribute to greater livelihood security for farmers and other actors. CIMMYT has developed the U-impact pathway as a framework to help meet this challenge. The adoption of CA practices is influenced on the supply side by the input delivery pathway from research to the farm (input value chains), and on the demand side by the characteristics of the farm household system and the marketing or value-adding chains from the farm to the consumer (output value chains). These three elements (input value chains, farm household system characteristics, and output value chains) can be viewed as the U-impact pathway. This pathway determines the rate and extent of

adoption of the CA practices, the magnitude of direct and indirect impacts, and the potential for feedback loops leading to improved functioning of the input and output value chains.

The adoption of CA practices is influenced by the nature and performance of the input value chains, which deliver inputs and services to the farm gate. They comprise CA service providers, the extension agents (both formal and informal; e.g., farmer-to-farmer) and, often, providers of complementary inputs such as credit and fertilizer. The availability of these “inputs” influences the rate of technology adoption and level of intensification. A case in point was the development of ZT drills in the rice-wheat systems in South Asia discussed above.

However, it is the decisions of farm women and men that ultimately will determine whether CA practices are adapted and adopted, leading to increased productivity, improved livelihoods, other primary and secondary impacts, and reduced poverty. Farm household decisions on technology adoption depend on the assessments of the expected changes in marginal costs, benefits and risk (both direct and indirect, as well as in cash and kind) in the specific farm system. Agriculture can, therefore, be viewed as an integrated technical-social system in which farmers and service providers create solutions to production and livelihood problems, often taking advantage of new opportunities through the modification of technologies and existing farming systems (Hall et al. 2005).

The process of identifying and meeting farmers’ needs is more efficient when an innovation system emerges. In order to target CA more effectively, research organizations and their partners need a better understanding of the innovation systems and impact pathways and networks that link research outputs to institutional outcomes and farm-level impacts, notably improved household livelihoods. This approach implies a shift of focus from crops to people-centered livelihoods and from linear technology selection and transfer to a nonlinear complex systems approach which explicitly recognizes feedback loops, farmer innovation, and systems’ dynamics and evolution.

The cases highlight that a main driver behind the rapid spread and widespread acceptance of CA is the combination of some “yield effect” and a substantial “cost saving effect,” which ensure the short-term profitability of adoption. However, farmers also need access to markets to dispose of surplus production at a reasonable price. Access to produce markets is often a critical determinant of adoption of agricultural technology and practices such as CA. Increasingly, researchers and development practitioners, who have traditionally focused on natural resource management, are taking a greater interest in issues around market access, CA is no exception (Hellin 2006).

A common thread in all three case studies is the research for development partnerships with, amongst others, agri-businesses that are active in the output (and input) chains. Furthermore, an analysis of this last leg of the U-impact pathway can help identify significant constraints to the adoption

of CA. For example, the output value chains in the rice-wheat systems of the north-west IGP in South Asia are characterized by widespread public intervention, particularly assured produce prices and marketing channels for rice and wheat grain. Although these foster intensification, they represent a major obstacle to the third component of CA—the practice of crop rotation with other crops such as legumes. The combination of secure produce markets and irrigation means that rice and wheat production are a low risk activity that has proven difficult to displace.

The impact of the adaptation and adoption of CA goes far beyond farmers. Beyond the direct food security benefits, welfare improvements derive from the improved distribution of benefits among different actors along both input and output value chains, including manufacturers, farmers, traders, and consumers. Further benefits accrue to farmers from on-farm diversification, and to other rural poor through the jobs created in the local farm and non-farm economy. This type of impact pathway analysis provides a plausible specification of the dominant links and critical roles of the key actors, leading to greater adoption of CA practices and generation of more local knowledge. An understanding of these links and roles allows for feedback and subsequently for the adaptation of behavior by actors in the chains to foster greater impact.

Last, as researchers we need to acknowledge that in the emerging economies, the capacity of farming to provide the sole means of survival for rural populations is diminishing fast. Whether because of declining relative crop prices, competition for land, poor access to markets, or declining productivity due to soil and land degradation, successful intensification and diversification may also lead to off-farm employment and even to a voluntary (cf. forced) exit from farming. Farmers are increasingly moving into rural non-agricultural work and the contribution of non-farm work to rural people's livelihoods should not be underestimated (Berdegue et al. 2000; Ellis 1999). It may be the case that adopters and adapters of CA eventually exit from farming. If they do so, it does not necessarily indicate that research efforts have been in vain. On the contrary it may be the case that the adoption of CA has enabled farmers to improve their incomes and to pursue a different (non-farm) livelihood outcome.

## CA ADOPTION

CA has reportedly spread widely with a global estimate of over 100 million ha of arable and permanent crops grown without tillage in CA systems—implying an annual rate of increase of 5.3 million ha globally since 1990 (Kassam et al. 2009). However, these remain expert estimates as reliably estimating and monitoring CA adoption has been fiendishly difficult—not least because of the varying interpretation of what constitutes CA and that

agricultural statistics generally do not report it or its associated practices. The relative complexity of adapting and adopting CA also makes it sites specific, making it inherently difficult to measure CA adoption let alone its impacts unambiguously (Erenstein 1999). This complexity thereby goes some way into explaining the apparent lack of universal truths in earlier reviews. For instance, a recent review of CA adoption studies concluded that there are few if any universal variables that regularly explain its adoption (Knowler and Bradshaw 2007). Similarly, an earlier review concluded that the economic benefits of the adoption of conservation tillage depended on site-specific factors undermining any comprehensive assessment (Uri 1999).

CA adoption thus far has been more widespread in temperate environments and for larger scale agriculture. Indeed, CA's relative complexity makes it easier for larger-scale farmers with their skills and resources to understand and make the necessary adaptations and bear the eventual transition risks. Furthermore, the cost saving nature of CA systems is of particular interest to commercial farmers and their keen interest in enhancing the bottom line through savings on machinery and fuel costs and eventual yield increases. This helps explain why within the same locality better-endowed farmers tend to be the first to adopt new technologies such as ZT (Erenstein and Farooq 2009). Still, as the case studies detailed in this article testify, CA can be successfully adapted to smallholder conditions and (sub)tropical environments, including both rainfed and irrigated systems.

Whenever farmers are provided with viable appropriate CA-based component technologies uptake can be rapid. A case in point is the rapid adoption of ZT wheat in the smallholder irrigated IGP in northern India, which echoes the spread of CA in rainfed commercial family farming in Brazil, eastern Paraguay and Argentina in the later 20th century. Although it remains somewhat sobering to note that even in the Brazilian ZT 'revolution' with its wealth of valuable ZT experience and technologies, numerous challenges remained with respect to smallholders so many years after its introduction (Bolliger et al. 2006).

The adaptation of soil and water conserving technologies and their adoption by farmers generally are already complex (e.g., Erenstein 1999; Hudson 1991; Tenge et al. 2004)—compounded by CA's technological complexities. Indeed, certain aspects of CA systems help explain why farmers—especially smallholders—may be slower to adopt than CA advocates would like. Smallholders often have short-term time horizons. Unless CA alleviates immediate crop growth constraints—for example, through water conservation when crops are drought stressed—CA is unlikely to result in an immediate yield increase. Even though farmers may understand that eventually yields will increase, the future benefits do not sufficiently outweigh their immediate needs (Suppe 1987).

CA being knowledge-intensive presents another major challenge for farmer acceptance (Kassam et al. 2009). While agricultural extension,

education and training can help many farmers maximize the potential of their productive assets, for example, through the use of CA systems, the promotion of CA has coincided with deep cuts to publicly-funded extension services in the developing world (Ajieh et al. 2008; Anderson and Van Crowder 2000). The breakdown of classical publicly funded agricultural research and extension services means that these services are now unable to address the needs of farmers living in marginal environments. In the majority of cases, however, the private sector has proven incapable of replacing previous state services due to high transaction costs, dispersed clientele, and low (or nonexistent) profits (Rivera and Cary 1997; Muyanga and Jayne 2008). In the absence of relevant and competent extension provision, one can expect lower adoption rates of a knowledge-intensive technology. New approaches to extension provision are needed along with a new consensus on the role of the public and private sectors and how extension provision for smallholders can be provided on a more sustainable basis and in a way that supports the emergence of the aforementioned agricultural innovation systems.

Another component of CA systems that can explain variation in farmer adoption rates is the provision of no-till equipment. A case in point are the three cases presented above—farmer adoption in each being dependent on the provision of locally viable seeders. Kassam et al (2009) also note that specialized no-till equipment, such as animal drawn and hand tools (including jab planters) originally developed in Brazil and the Americas, are being exported to Africa and Asia where it is being adapted for local use and manufacture. The private sector is likely to be key player in the sustainable provision of appropriate no-till equipment as expounded by more recent thinking on small-scale manufacturing and the provision of business development services (Sievers and Vandenberg 2007). In the absence of competing private sector manufacturers of no-till equipment or an efficient publicly subsidized program, it may be the case that farmers do not have access to inputs that are critical to the success of CA systems.

The reduction in tillage may imply the need for alternative weed control measures, including herbicides. This may be less of an issue in intensive systems—a case in point being ZT wheat in the irrigated rice-wheat systems discussed above. In more extensive systems though, labor and cash constraints can determine farmers' acceptance of CA-based practices especially if farmers are unable to purchase labor-saving technologies such as herbicides. Giller et al (2009) have referred to weeds as the Achilles heel of CA in Africa precisely because weed control is often laborious and costly in the first years and may, thus, imply a greater reliance on herbicides. If farmers have ready access to reasonably priced herbicides via efficient and effective input supply chains then weeds need not be a constraint to the use of CA systems. In fact, herbicide use may spread independently from CA, as farmers increasingly diversify their livelihoods with off-farm

income-generating activities and thus need to alleviate labor constraints at different times of year.

A final important factor influencing farmer acceptance and adoption of CA is the relative ease with which CA practices can be adapted and incorporated into existing farming systems. Particularly in extensive systems the limited availability of crop residues can be an important constraint for adoption of CA practices, especially where there are competing demands for crop residues for mulching, fodder, fuel, or construction material. Individual interest may also be constrained by the need for collective action—as in instances where mulch retention is constrained by the prevalence of stubble grazing, and wildfires.

CA systems are relevant to a variety of agroecological and socioeconomic conditions. Its relevance, however, and the farmer's willingness (and ability) to practice CA, is determined by a unique combination of the agroecological and socioeconomic condition found in his or her farming system. This makes the identification of the situations when CA can offer major benefits both a research challenge (Giller et al. 2009) and a challenge to researchers who may find it hard to accept that matching CA systems to optimum agroecological and socioeconomic conditions is as much art as it is science. Such matching can best be achieved through an innovation systems approach that fosters dynamic interactions among researchers, extension agents, equipment manufacturers, input suppliers, farmers, traders, and processors. Critically, this depends on learning processes, feedback loops, and iterative interactions that are decidedly nonlinear (Spielman et al. 2008). Only then is a targeted adaptation process likely to create viable CA-based options.

## CONCLUSION

CIMMYT's experiences with CA are testament to the wide adaptability of CA systems. CA can generate clear economic benefits, including substantial reductions in production costs and increased yields. Yields are also stabilized in rainfed areas thus reducing farmer risk. Moreover, there are potentially enormous environmental benefits stemming from savings of irrigation water, diminished weed pressure, improved soil management, and reduced emission of green house gases. The environmental dividends from the further spread of CA in Asia, notably the irrigated areas of India and China, will be immense, as well as securing low cost food for the poor masses. The widespread adaptation and adoption of CA in rainfed smallholder agriculture in Africa would help address the poverty complex of poor farm assets, degraded resources, vulnerability, and lack of diversification.

The case studies and wider literature however also reiterate the substantial challenges in terms of targeting, adapting and adopting CA—particularly

for smallholders in the (sub)tropics. As institutions grow stronger, markets open for more diversified produce and policies tilt towards improved resource management; the environment for CA adaptation and adoption is thereby progressively improving. Moreover, the advantages of CA over conventional tillage systems will grow as fresh water becomes scarcer in irrigated systems, as volatility increases in rainfed systems and as climate change begins to bite. CA is not a fixed technological recipe for application across different farming systems: to the contrary, CA systems are best developed in situ through a multi-stakeholder adaptive learning process. Experience shows that farmers, researchers, service providers and machinery manufacturers need to be linked in an innovation system which fine-tunes equipment and crop management while strengthening local institutions to create viable CA-based options that are technically sound, economically attractive and socially acceptable.

## NOTE

1. Other examples of CIMMYT's collaborative CA work not covered here include rainfed maize-based systems in Central America; soybean-wheat double-crop systems in Paraguay and Bolivia; wheat-based systems in the inter-Andean valleys of Bolivia and the highlands of Mexico and Ethiopia; and wheat-based systems in northern Kazakhstan (e.g., Karabayev and Suleimenov 2009).

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