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Zero Tillage in the Rice-Wheat Systems of the Indo-Gangetic Plains

A Review of Impacts and Sustainability Implications

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2020 Vision Initiative

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A total of 20 case studies are included in this project, each one based on a synthesis of the peer-reviewed literature, along with other relevant knowledge, that documents an intervention's impact on hunger and malnutrition and the pathways to food security. All these studies were in turn peer reviewed by both the Millions Fed project and IFPRI's independent Publications Review Committee.

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Notices

[1] Effective January 2007, the Discussion Paper series within each division and the Director General's Office of IFPRI were merged into one IFPRI–wide Discussion Paper series. The new series begins with number 00689, reflecting the prior publication of 688 discussion papers within the dispersed series. The earlier series are available on IFPRI's website at www.ifpri.org/pubs/otherpubs.htm#dp.

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ABSTRACT

This paper reviews the success of zero-tillage wheat in the rice-wheat systems of the Indo-Gangetic Plains. Diffusion of the zero- tillage technology increased in the last decade, particularly in northwest India. In 2008, in India alone, the aggregate area in zero- or reduced- tillage wheat amounted to 1.76 million hectares, and it was used by 620,000 farmers. Zero-tillage wheat allows for a drastic reduction in tillage intensity, resulting in significant cost savings as well as potential gains in wheat yield through earlier planting of wheat. Wheat farmers who adopted zero tillage could enhance their farm income by about US$100 per hectare. The cost-saving effect alone makes zero tillage profitable and is the main driver behind its spread. The potential environmental benefits of zero tillage have yet to be fully realized and imply tackling the challenge of reducing tillage for the rice crop that follows wheat, retaining crop residues as mulch, and diversification of crops. Equity also poses a challenge: there is a need to extend the gains more rigorously to the less endowed areas and farmers. Zero tillage's impact has been achieved through an intervention that has proven privately attractive; an enabling process that combined elements of persistence, flexibility, inclusiveness, and facilitation; and a context that implied the need for change. To replicate and extend this success, viable and dynamic innovation systems should be developed that can deliver and adapt interventions such as zero tillage. Addressing the existing knowledge gaps regarding zero tillage's socioeconomic, livelihood, and environmental impacts would enhance the ability to outscale in a cost-effective, equitable, and sustainable manner.

Keywords: Millions Fed, Food Security, Zero Tillage, Indo-Gangetic Plains, IGP, Rice, Wheat

1. INTRODUCTION

An Overview of the Case for Zero Tillage

The stagnation of productivity growth in the rice-wheat systems of the Indo-Gangetic Plains in South Asia has led to increased calls for technologies based on conservation agriculture. To date, the most significant progress has been made by addressing the challenge of reducing tillage for wheat using tractor-drawn zero-tillage drills to seed the wheat crop into unplowed fields. The origin of zero-tillage wheat in rice-wheat systems can be traced to the importation of the prototype technology and adaptive research in the mid- to- late 1980s, followed by the subsequent creation of a local manufacturing capacity to supply adequate and affordable zero-tillage drills. Concerted efforts by an array of stakeholders that spanned public and private sectors and national and international research systems and included several persevering champions provided the institutional support for the technological opportunity to materialize.

The diffusion of the technology has accelerated in the early years of the 21st century, particularly in the northwest Indo-Gangetic Plains of India, where the combined zero- and reduced-tillage wheat area seems to have stabilized at between a fourth and a fifth of the wheat area. Several factors make it problematic to reliably measure zero-tillage adoption and impacts in the Indo-Gangetic Plains. We estimate that in 2008 the aggregate zero/reduced tillage wheat area amounted to 1.76 million hectares and was used by 620,000 farmers. Zero-tillage wheat allows for a drastic reduction in tillage intensity, with significant costs savings as well as potential wheat yield gains through planting of the wheat crop at a better time. Wheat farmers who adopt zero tillage are the main beneficiaries, enhancing their farm income by about US$100 per hectare. The cost-saving effect alone makes zero tillage profitable and is the main driver behind its spread. Viable dynamic systems for diffusion of innovations have been key to the success of zero tillage in India, including a vibrant manufacturing base for zero-tillage drills and drilling service providers.

Farmers in the Indo-Gangetic Plains have primarily realized the potential efficiency gains associated with zero tillage (summarized in Table 1). However, no robust data are yet available on zero tillage's impacts on household food security and nutrition. So far, the impacts of zero tillage have been primarily limited to the wheat crop: the subsequent rice crop is still intensively tilled. Zero-tillage wheat also does not necessarily imply the retention of crop residues as mulch nor does it necessarily entail an increased reliance on herbicides. The potential environmental benefits of conservation agriculture have yet to be fully realized: to reap these benefits the challenges of reducing tillage for rice as well as wheat, retaining crop residues, and diversifying crops must be met. Equity has also posed a challenge so far, and gains need to be extended more rigorously to the less endowed areas and farmers, which calls for a better understanding of livelihood implications and dialogue and participation of stakeholders.

Zero tillage's impact in the Indo-Gangetic Plains has been achieved through an intervention that proved privately attractive; an enabling process that combined elements of persistence, flexibility, inclusiveness, and facilitation; and a context that implied a need for change. To replicate and extend the success so far achieved, we must develop viable and dynamic innovation systems that can deliver and adapt interventions such as zero tillage. Addressing the knowledge gaps concerning zero tillage's socioeconomic, livelihood, and environmental impacts would enhance the ability to do so in a cost-effective, equitable, and sustainable manner.

2. ZERO TILLAGE IN RICE-WHEAT SYSTEMS

The Green Revolution transformed the Indo-Gangetic Plains, which spread from Pakistan through northern India and the *terai* (plains) region of Nepal to Bangladesh, into the cereal basket of South Asia. 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 and the advent of rice-wheat systems, which now cover an estimated 14 million hectares in the region (Gupta et al. 2003; Gupta and Seth 2007; Timsina and Connor 2001). Over the past decade, however, factor productivity growth has stagnated (Kumar et al. 2002;Ladha et al. 2003;Prasad 2005; Duxbury 2001; Kataki, Hobbs, and Adhikary 2001), leading to concerns over national food security and lagging rural economic growth. This has led to a quest for technologies that conserve resources, reduce production costs, and improve production while sustaining environmental quality (Erenstein et al.2008a; Gupta and Sayre 2007; Gupta and Seth 2007; Hobbs and Gupta 2003a). One such promising technology is zero tillage: the seeding of a crop into unplowed fields, also known as no till, direct seeding/drilling, or conservation tillage (Erenstein 2002; Erenstein et al. 2008b). Zero tillage typically saves energy, helps reverse soil and land degradation (such as decline of soil organic matter, soil structural breakdown, and soil erosion), and leads to more efficient use of water and other inputs (Erenstein and Laxmi 2008).

Zero-tillage planting of wheat after rice has been the most successful resource-conserving technology to date in the Indo-Gangetic Plains, particularly in northwest India and to a lesser extent the Indus plains in Pakistan (Erenstein et al. 2007c; Erenstein and Laxmi 2008). The interest in zero tillage in the Indo-Gangetic Plains originated from diagnostic studies that highlighted the importance of time conflicts between rice harvesting and wheat planting in both northwest India (Fujisaka, Harrington, and Hobbs 1994; Harrington et al. 1993) and Pakistan (Byerlee et al. 1984). Wheat is grown in the cool and dry winter and is the traditional mainstay of food security in the northwest Indo-Gangetic Plains. Rice is grown during the warm monsoon season, but its introduction and widespread cultivation in the northwest area only occurred in recent decades during the Green Revolution. Zero-tillage wheat has a number of advantages, alleviating a number of constraints in the rice-wheat system: it permits earlier wheat planting, helps control obnoxious weeds like *Phalaris minor*, reduces costs, and saves water (Erenstein and Laxmi 2008).

The prevailing zero-tillage technology in rice-wheat systems in the area is use of a tractor-drawn seed drill with 6 to 11 inverted-T tines to seed wheat directly into unplowed fields with a single pass of the tractor. This specialized agricultural machinery was originally not available in South Asia. Creating the local manufacturing capacity to supply adequate and affordable zero-tillage drills was a key component in the diffusion of the technology. In Pakistan, adaptive research designed to make zero-tillage methods suitable for local conditions started during the mid 1980s, following the importation of a prototype drill with inverted-T openers from Aitcheson Industries, New Zealand, for use by national program scientists from the National Agricultural Research Center and by the International Maize and Wheat Improvement Centre [CIMMYT]. In India, the same inverted-T openers were introduced in 1989 by CIMMYT, and in 1991 a first prototype of the Indian zero-tillage seed drill was developed at G. B. Pant University of Agriculture and Technology, Pantnagar. In both countries, a collaborative program for further development and commercialization of zero-tillage drills by small-scale farm machinery manufacturers was initiated by the national agricultural research system in collaboration with CIMMYT and subsequently the Rice-Wheat Consortium of the Indo-Gangetic Plains, and its history has been variously documented (Ekboir 2002; Erenstein and Laxmi 2008; Harrington and Hobbs 2009). Surface seeding is one option for employing zero tillage without the use of a tractor or seed drill (Tripathi et al. 2006), but its use is largely confined to low-lying fields with drainage problems in the Eastern Gangetic Plains.

The promotion of zero tillage in India has been particularly successful, benefiting from the timely congruence of a profitable technological opportunity and the several key champions who encouraged adoption (Laxmi, Erenstein, and Gupta 2007a). Several factors proved crucial to its success in India (Seth et al. 2003:67). A local manufacturing capacity was developed to produce and adapt zero-tillage 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, and a guarantee for 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. Strong support from state and local government officials helped with dissemination, including the provision of a subsidy to lower the investment cost and initiate extensive on-farm demonstrations and trials. The Rice-Wheat Consortium 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 (Erenstein 2009a).

The success of zero tillage in India highlights the importance of institutional support for a technological opportunity to materialize. In Pakistan's Punjab Province, the agroecology and system constraints are relatively similar, and favorable experimental findings led to a pilot production program in the 1990s to promote the use of zero tillage (Aslam et al. 1993). But the spread of zero tillage has been significantly slower there, hampered by institutional controversies within the national system and a lesser presence of the Rice-Wheat Consortium, among other things (Erenstein et al. 2007a).

There is a wealth of information on zero tillage in the Indo-Gangetic Plains, particularly in India (see Erenstein and Laxmi 2008 for a recent review; Gupta et al. 2003; Hobbs and Gupta 2003a; and compendium volumes such as Abrol, Gupta, and Malik 2005; Malik et al. 2002; Malik et al. 2005a; Malik et al. 2005b). Most of the documented evidence relates to the northwestern Indo-Gangetic Plains, where intensive rice-wheat systems prevail and where adoption has been more extensive than in other areas so far. There is ongoing research and development (R&D) work in the eastern Gangetic plains of India (Bihar, Uttar Pradesh, and West Bengal), Nepal *terai*, and Bangladesh. Initial results in the eastern plains are encouraging but not yet well documented or widely published. This paper synthesizes the documented experiences with zero tillage in the rice-wheat systems across the Indo-Gangetic Plains. It will thereby specifically focus on zero tillage's impact (particularly diffusion, adoption, and farm-level impacts), its sustainability dimensions (financial and fiscal, environmental, and social and political), and the lessons learned.

3. ZERO TILLAGE'S IMPACT IN RICE-WHEAT SYSTEMS

Diffusion and Adoption of Zero Tillage

Adoption of zero tillage for wheat in South Asia started in the second half of the 1990s and accelerated in the early years of the 21st century. Experts estimate that the combined zero/reduced tillage wheat area in the Indo-Gangetic Plains amounted to some 2 million hectares in 2004/05 primarily in India. But the actual extent of zero-tillage diffusion in the Indo-Gangetic Plains is not precisely known. Zero-tillage research and the associated data collection and reporting have both increased and improved in the past several years in the area. However, most studies primarily report on the technical aspects of zero tillage at the plot level and often are based on trial data (on-station and on-farm) (Erenstein and Laxmi 2008). Many of the farm surveys are not based on a robust sampling frame that would allow for unbiased diffusion estimates. Instead, most farm surveys contrast a sample of zero-tillage adopters with nonadopters (see, for example, Bakhsh, Hassan, and Maqbool 2005; Jamal, Akhtar, and Aune 2007; Sarwar and Goheer 2007; Singh 2008). Reliable and empirically based zero-tillage diffusion indicators are particularly scarce and problematic. Lacking other estimates, the expert estimates of zero tillage adoption are often repeated and cited by others. However, in the process, two important underlying qualifications are often omitted – that is, they are expert estimates and not empirically grounded, and they reflect estimated zero- tillage drill use irrespective of tillage intensity.

A problem with estimating zero-tillage adoption is that it is a cultural practice that is sparsely reported in agricultural statistics and studies. It is also ambiguously interpreted, with the term often used interchangeably for the cultural practice and the seeding implement. Yet whereas most zero tillage depends on the use of a zero-tillage seed drill, the practice is not unambiguously embodied in this machinery, as the drills are also used on fields where tilling is reduced and even on conventionally tilled fields. Furthermore, zero tillage is also variously used, including variations over seasons and within farms, with farmers often using it for one part of their farm, while adhering to more intensive tillage in other parts. This all makes the reliable measurement of zero tillage adoption and impacts problematic.

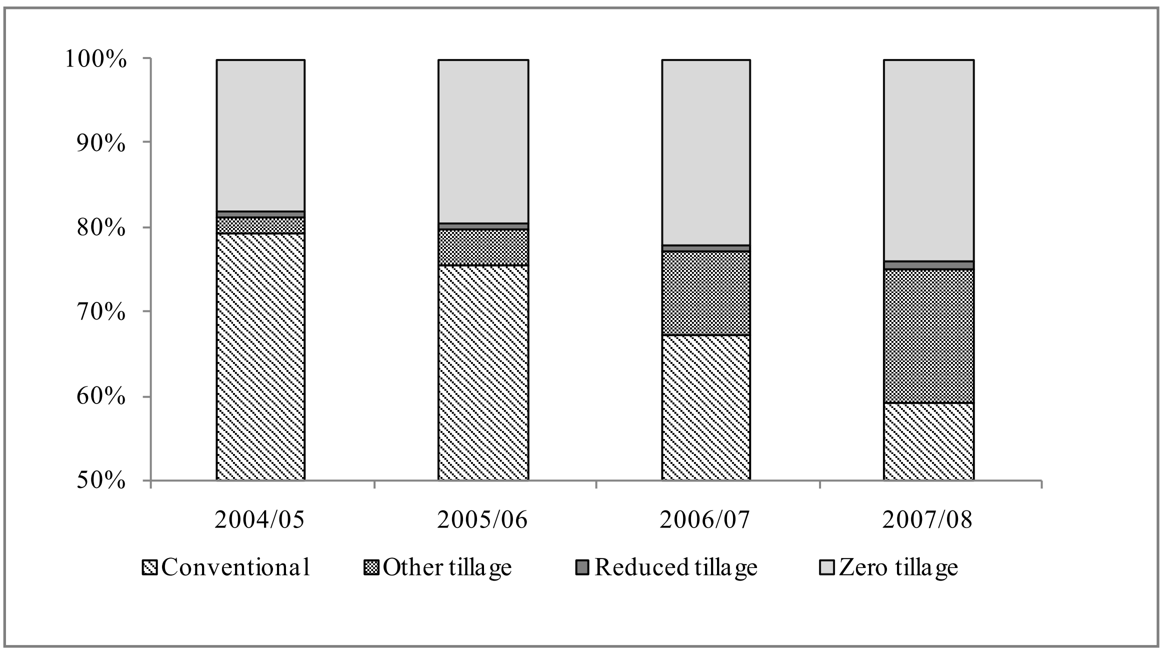
Surveys of manufacturers of zero-tillage drills revealed that the manufacturing capacity is spatially concentrated in the rice-wheat belt in the northwest Indo-Gangetic Plains, particularly Haryana (India) and the Indian and Pakistan Punjab (Erenstein, Malik, and Singh 2007; Farooq et al. 2007). The first commercial zero-tillage drills thereby originated in the traditional agricultural machinery manufacturing centers in the Green Revolution heartland. The three locations (Haryana, Indian Punjab, and Pakistan Punjab) show a relatively similar increase in the number of manufacturers over time, both in absolute and relative terms. However, aggregate sales figures of the surveyed drill manufacturers in Pakistan Punjab are a fraction of those in Haryana and Indian Punjab. By the end of 2003, a cumulative total of 15,700 zero-tillage drill machines had been sold by the 50 surveyed manufacturers in India, with Haryana registering more than half the reported sales in each year. This compares with the 2,000 zero-tillage drills sold by 31 manufacturers in Pakistan Punjab. Whereas annual sales figures for zero-tillage drills for surveyed manufacturers in India were still on the increase, the sales figures in Pakistan Punjab were relatively flat, with peak sales in 2002. The wider manufacturing base and significant growth in sales implies healthy competition between manufacturers in India, with favorable implications for price and quality and generally lighter drills. The average sales price of a zero tillage drill in 2003 amounted to US$325 in India as against US$559 in Pakistan (Erenstein et al. 2007a).

Farm household surveys in 2003/04 confirmed significant adoption of zero-tillage wheat in the rice-wheat systems of northwest Indo-Gangetic Plains: 34.5 percent of sample farmers in India's Haryana and 19 percent in Pakistan's Punjab (Erenstein, Malik, and Singh 2007; Erenstein et al. 2007a; Farooq, Sharif, and Erenstein 2007). The farms were typically only partial adopters of zero tillage—that is, only a share of their wheat area was put under zero tillage, with the remaining area still under conventional tillage. This implies the actual area under zero tillage is typically less than the rate of adoption in terms of number of farmers.

The expert estimates, the manufacturers surveys, and farm surveys in India and Pakistan agree that zero tillage has picked up since 2000, but the empirical surveys suggest a much slower uptake and subsequent stagnation in Pakistan (Erenstein et al. 2007a). This reiterates the need for empirical ground truthing of the technology's uptake and the need for robust and complementary diffusion indicators.

During the winter/rabi season of 2007/08 the rice-wheat villages in Haryana surveyed earlier by Erenstein, Malik, and Singh (2007) were revisited (Erenstein 2009a). These visits show that the zero-tillage wheat area continued to increase, albeit at a slow pace, from an average share of village wheat area of 18 percent in 2004/05 to 24 percent in 2007/08 (Figure 1). As reported earlier (Erenstein, Malik, and Singh 2007), reduced tillage area in these villages was still marginal, with farmers using either zero tillage or conventional tillage. However, the revisit highlighted the rapid increase in another new tillage system, primarily use of a tractor-drawn rotavator (other tillage in Figure 1). The rotavator typically implies a single pass of shallow intensive tillage, which incorporates crop residues and pulverizes the soil. It thereby may reduce the number of passes, compared to conventional tillage, but its tillage intensity goes against the tenets of conservation agriculture (Erenstein 2009a).

Figure 1. Recent evolution of wheat tillage in rice-wheat systems in Haryana, India (village survey findings, n=50)



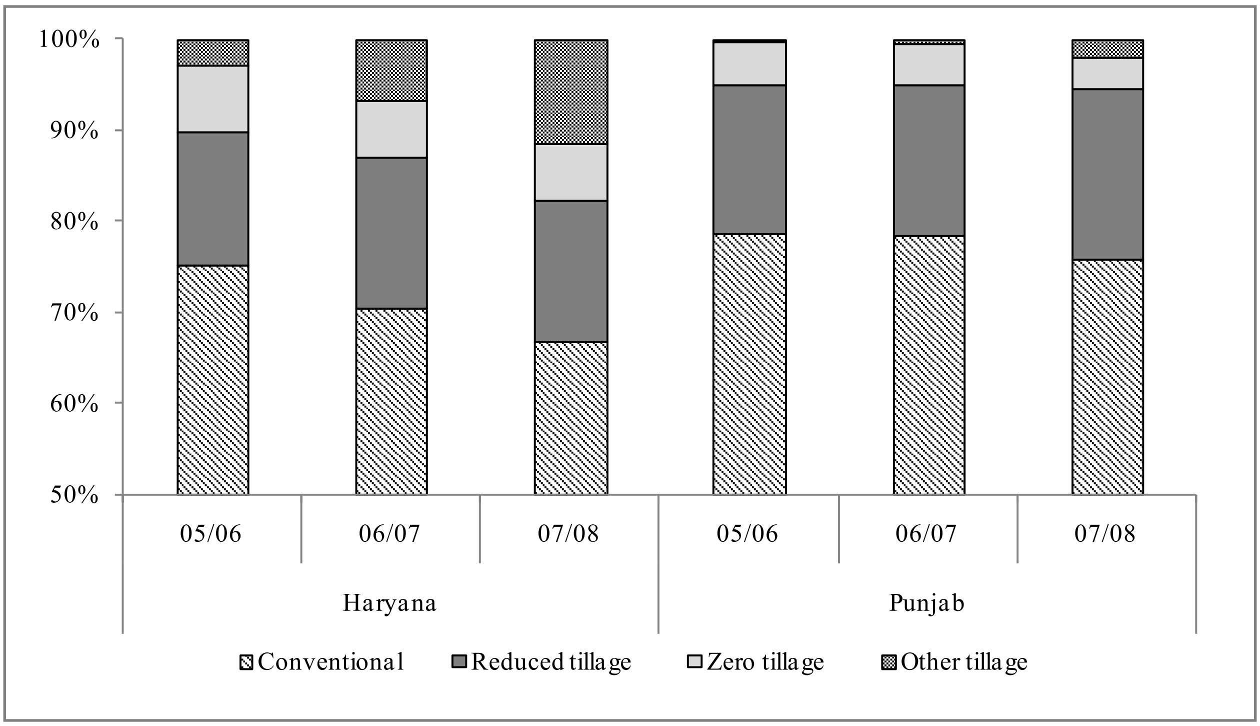
Source: Erenstein 2009a.

In the winter/rabi season 2007/08, an additional wheat tillage monitoring survey was conducted across 120 randomly selected villages in Haryana and Indian Punjab. This study provided a more representative random sample of wheat-cultivating villages, and included nonrice-wheat systems. Compared with the Haryana rice-wheat study area (Figure 1), the results show some marked divergences (

Figure 2). First, the share of zero-tillage area is significantly lower – both in Haryana and Punjab – and shows a small decline over the period 2005/06 to 2007/08. Second, the reduced-tillage area is a multiple of the zero-tillage area and shows a small increase in both states. Extrapolating these estimates would imply a combined zero/reduced tillage wheat area of 1.26 million hectares in Haryana and Indian Punjab in 2007/08. With an average area of 3.5 hectares of zero/reduced tillage wheat per adopter, this amounts to an extrapolated 360,000 farmers in the Haryana and Punjab alone. The results also suggest that after the initial rapid spread of zero tillage in the northwest Indo-Gangetic Plains, the zero/reduced tillage wheat area seems to have stabilized there at between a fifth and a fourth of the wheat area. The study also shows that, particularly in Haryana (

Figure 2), and similar to the other study (Figure 1), there was a marked increase in other tillage systems (primarily rotavator use). The advent of the rotavator merits follow- up research and active engagement with regional stakeholders as it offsets much of the gains implied by more conservation agriculture-based resource-conserving technologies like zero/reduced tillage (Erenstein 2009a).

Figure 2. Recent evolution of wheat tillage systems in Haryana and Punjab, India (village survey findings, n=120)



Source: Erenstein 2009a.

Adoption in the Eastern plains is still in its initial stages with a dearth of empirically based adoption estimates. A random village survey in 2005 found 13 percent of farm households using zero/reduced tillage in the northwestern rice-wheat belt, with still negligible adoption rates elsewhere in the Indian Indo-Gangetic plains (Erenstein et al. 2007b, 2007c). In 2006, a village survey of primarily project villages in India reported zero/reduced tillage adoption rates of 18 percent of farm households in the northwestern plains and 5 percent in the eastern plains (Teufel, Erenstein, and Samaddar 2007). In 2008 a regional village survey reported zero/tillage use in 14 percent of wheat area in project villages in the northwestern plains (Pakistan and India), 12 percent in the central plains (India and Nepal), and none in the lower Gangetic plains of Bangladesh (Singh, R. et al. 2009). Our guesstimate of zero/reduced tillage area in the Indian Indo-Gangetic states, excluding Punjab and Haryana, would be 0.5 million hectares. Based on an average of 1.9 hectares per adopting farm in the Indian project site of Ballia, Eastern Uttar Pradesh (Singh, R. et al. 2009), this would amount to some 260,000 users. For the Indian Indo-Gangetic Plains, the aggregate zero/reduced tillage area in 2008 would thus amount to an estimated 1.76 million hectares and 620,000 farmers (Table 1).

Table 1. Summary of key impacts of zero tillage in India's Indo-Gangetic Plains

Indicator	Value
Households directly affected (estimate)	620,000
Extent of adoption (zero/reduced tillage, estimate)	1.76 m ha
Production cost saving [a]	US$ 52/ha
Increase in crop yields [a]	5-7% (140-200 kg/ha)
Increase in farm income from wheat production [a]	US$97/ha
Increase in real household incomes	US$180-340/farm
Increase in food production	0.7% (343,000 tons)

Sources: [a] Erenstein and Laxmi 2008.
[a] Author's estimates based on research reviewed in the text.

Farm-level Impacts of Zero Tillage

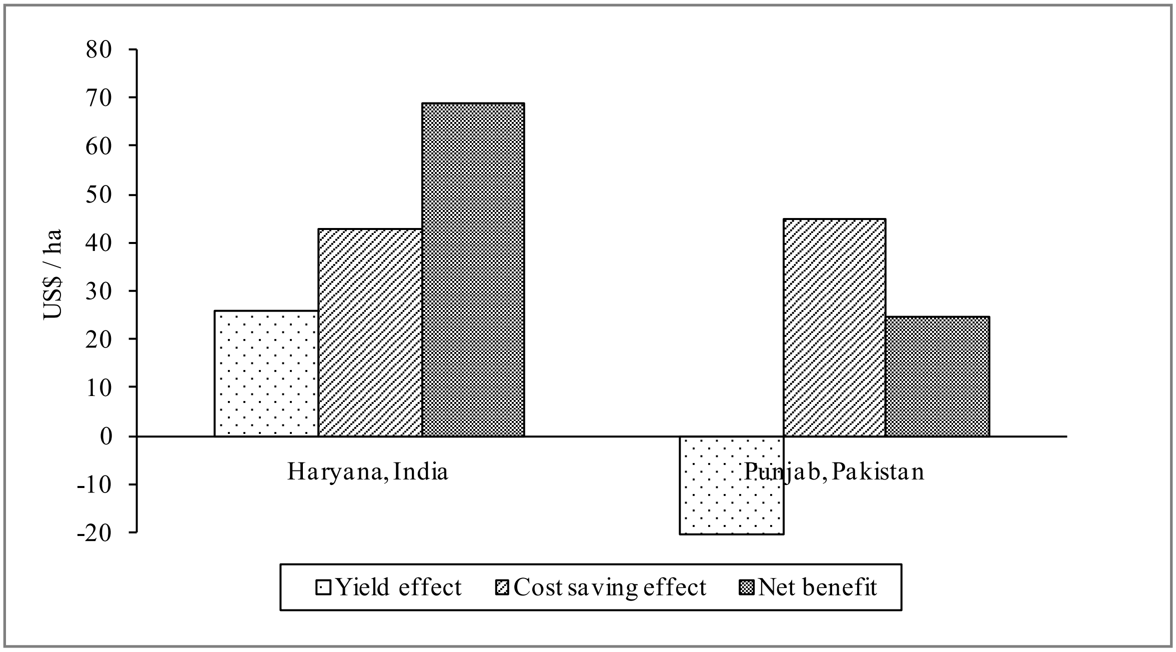
Erenstein and Laxmi (2008) provide a comprehensive review of the impacts of zero-tillage wheat in India's rice-wheat systems, including effects on land preparation and crop establishment, water use, soils and biotic stresses, yields, and cost savings and profitability. Their review shows that zero-tillage wheat after rice generates substantial benefits at the farm level by enhancing farm income from wheat cultivation (US$97 per hectare) through the combined result of a yield effect and a cost-saving effect (Table 1).

The cost-saving effect (US$52 per hectare) primarily reflects the drastic reduction in tractor time and fuel for land preparation and wheat establishment (Erenstein and Laxmi 2008). The tractor-drawn zero-tillage drills allow tillage intensity to be drastically reduced for the wheat crop from eight tractor passes to a single tractor pass (Erenstein et al. 2007a; Erenstein et al. 2008a). This implies a significant, immediate, and recurring cost saving, which makes adoption profitable (corresponding to a 15–16 percent saving on operational costs in Erenstein et al. 2007a).

The review of zero tillage in India found a yield effect amounting to a 5–7 percent yield increase for wheat being reported across studies (including on-station trials, on-farm trials, and surveys in Erenstein and Laxmi 2008). This provides a further boost to the returns to zero tillage. The yield effect, if any, is closely associated with enhanced timeliness of wheat establishment after rice. Heat stress at the end of the wheat season implies that the potential wheat yield is reduced by 1-1.5 percent per day if planting occurs after mid November (Hobbs and Gupta 2003a; Ortiz-Monasterio, Dhillion, and Fischer 1994). It is estimated that about a third of the wheat area in the Indian Indo-Gangetic Plains is sown late—often linked to late maturing Basmati rice in the northwestern Indo-Gangetic Plains (including Pakistan Punjab) and generally late rice harvesting in the eastern plains—and zero tillage potentially would alleviate this by allowing for timelier establishment.

Literature on zero tillage in Pakistan shows it to also be profitable there, based on a similar combination of yield gains and cost savings (Bakhsh, Hassan, and Maqbool 2005; Choudhary et al. 2002; Jamal, Akhtar, and Aune 2007; Kahlown, Gill, and Ashraf 2002; Sarwar and Goheer 2007) and widespread late planting of wheat (Akhtar 2006; Farooq, Sharif, and Erenstein 2007). In the case of Haryana (India), the large farm surveys confirmed both a significant yield effect and cost-saving effect (Figure 3), thereby making adoption worthwhile and providing a much needed boost to the returns to wheat cultivation (Erenstein, Malik, and Singh 2007). Similar farm surveys in Pakistan Punjab found zero tillage to be primarily a cost-saving technology for wheat cultivation, with no significant yield effect (Figure 3–(Erenstein et al. 2007a; Erenstein et al. 2008a; Farooq, Sharif, and Erenstein 2007). In fact, the lack of a positive yield response was a major contributor to the slower adoption in Punjab and merits follow-up research.

Figure 3. Financial advantage of zero tillage over conventional tillage for wheat on farms adopting zero tillage in 2003/04 in Haryana, India, and Punjab, Pakistan (farmer survey findings, n=225)



Source: Erenstein 2009a adapted from Erenstein et al. 2008a).

Whereas zero tillage enhances income for wheat farmers in the Indo-Gangetic Plains, less is documented or known about the associated impacts on household food security and nutrition. The time and additional resources saved are used by the adopting farm households for various productive, social, and leisure purposes (Erenstein and Farooq 2009; Erenstein and Laxmi 2008; Laxmi, Erenstein, and Gupta 2007a). In the Pakistan Punjab, zero tillage reportedly increased families' food consumption, probably through higher disposable income (Erenstein and Farooq 2009; Farooq, Sharif, and Erenstein 2007). In eastern Uttar Pradesh, India, zero tillage generated additional income through sales of the increased production (Jafry 2007). Future research may attempt to more rigorously document such impacts on household food security and nutrition. Still, such endeavors will present major challenges, starting with the somewhat fuzzy nature of measuring adoption and immediate crop-level impacts of such crop management practices. The cost-saving effect is relatively robust, but its household impacts will be difficult to trace, in view of its pecuniarily fungible nature in relation to outlays forgone and the difficulty of disentangling the various confounding factors. Tracing the impacts of a positive yield effect may be somewhat easier, but such an effect is not always realized by farmers.

Little has been documented about the gender-specific dimensions of zero tillage's impact. To a large extent this is a reflection of zero tillage having primarily spread in the northwest Indo-Gangetic Plains. In this area, farm households are typically headed by males, with women having limited participation in field-based crop activities and being primarily engaged in livestock and homestead-based activities (Erenstein et al. 2007b; Erenstein and Farooq 2009). The few available studies report that women generally appreciated zero tillage. They acknowledged that after zero tillage adoption, there was less anxiety at the time of wheat field preparation, and this resulted in more peace at home (Erenstein and Laxmi 2008; Laxmi, Erenstein, and Gupta 2007a). One study also reported more food being available for women and improved family diets (Joshi et al. 2007b). Some studies have indicated that women farmers are dependent on their families for knowledge and information about new technologies like zero tillage (Jafry, Ahmad, and Poswal 2006; Jafry 2007; Joshi et al. 2007b).

Zero tillage was originally perceived as potentially generating higher yields at a lower production cost, while being an environmentally friendly practice that saves water and soil (Gupta et al. 2002; Hobbs, Giri, and Grace 1997; Hobbs and Gupta 2003b). The subsequent literature generally confirms significant zero tillage-induced resource-saving effects in farmers' fields in terms of diesel, tractor time, and cost savings for wheat cultivation (Erenstein et al. 2008a; Erenstein and Laxmi 2008). Zero tillage saves irrigation water through the combined effect of allowing wheat to be planted without pre-irrigation and shortening the duration of the first irrigation, as surface irrigation water flows faster across a nontilled field. Water savings in farm surveys are, however, less pronounced than expected from the initial on-farm trial data (they are linked to adopters generally reporting a similar number of irrigations and the inability to control for all confounding factors in survey data) but in any case water use is modest compared with the subsequent rice crop (Erenstein et al. 2008a). Other technologies such as laser leveling can generate more substantial water savings and have recently been taken up by farmers (Jat et al. 2009). Despite zero tillage's ability to reduce turnaround time, farm surveys also did not find that wheat was established earlier, thereby reducing the likelihood of obtaining higher yields with zero tillage (Erenstein et al. 2008a; Tahir and Younas 2004). A better understanding of why farmers did not capitalize on the potential of zero tillage to sow the wheat crop earlier merits follow-up research.

An important issue with zero tillage is that it is a component technology of conservation agriculture. Its current application to only one of the two cropping seasons, without adequate residue management or crop rotation, forgoes much of the environmental benefits associated with conservation agriculture, which is discussed in the next section. In the end, the prime driver for farmers' adoption of zero tillage is monetary gain, not water savings or natural resource conservation (Erenstein et al. 2008a).

Another issue is that the gains currently realized in farmers' fields have long been based on systems built on the premise of intensive tillage. Specifically selecting wheat varieties under zero-tillage conditions can thereby boost the benefits of zero tillage (Joshi et al. 2007a; Rajaram et al. 2007). Similarly, wheat is adversely affected by the puddling (wet tillage) of the previous rice crop, and implications for the zero-tillage wheat yield are likely to be more favorable when farmers forgo seasonal puddling of the rice crop (Erenstein and Laxmi 2008).

4. ZERO TILLAGE'S SUSTAINABILITY IN RICE-WHEAT SYSTEMS

Financial and Fiscal Sustainability

Laxmi, Erenstein, and Gupta (2007a; 2007b) show that investments in the research and development of zero/reduced tillage by the Rice-Wheat Consortium of the Indo-Gangetic Plains and CIMMYT were highly beneficial. They assume that these investments accelerated adoption of zero/reduced tillage by five years, only taking into account supply-shift gains (excluding social and environmental gains). These investments thereby yielded significant economic benefits: a net present value of US$94 million, a benefit–cost ratio of 39, and an internal rate of return of 57 percent. Significant positive spillovers of investments in R&D on zero tillage—both previous and from elsewhere—contributed to the high returns. The zero-tillage case thereby highlights the potential gains from successful technology transfer and adaptation, particularly for a technology that has been widely recommended.

The cost savings, particularly when combined with a yield increase, imply that the returns to adoption of zero tillage are quite robust, thereby significantly reducing the risk of adoption (Erenstein and Laxmi 2008). Still, in the early diffusion stages, prospective owners of zero-tillage drills used in rice-wheat systems have tended to complain that the machine can only be used during wheat crop establishment (sitting idle for most of the year). This reflects the prevalence of rice-wheat systems in which rice is typically still being transplanted. However, many of the current zero-tillage drills can effectively seed different crops, including direct-seeded rice. However, even if drills are only used during the limited operational window of wheat establishment, drills can be effectively and economically used by tractor service providers on multiple farms. For instance, a survey of zero-tillage drill owners in Haryana showed that each drill had on average planted 42 hectares in a single wheat season (Punia et al. 2002). The investment cost of a zero-tillage drill can also be rapidly recovered within two seasons through the cost savings alone (Erenstein et al. 2007a).

In India there is a tradition of subsidizing agricultural machinery. Some state governments (such as Haryana) therefore provide a subsidy of about 25 percent on the purchase price of a new zero-tillage drill (Ekboir 2002). Such investment subsidies may enhance farmers' access to new implements, but they typically add to the transaction cost, imply opportunity costs, and reinforce paternalistic expectations that reduce farmers' initiative as they wait for subsidies to materialize. Whether conservation agriculture-based technologies like zero tillage should be entitled to a subsidy remains an open question, as the comprehensive social gains need to be weighed against the social costs (Erenstein and Laxmi 2008). In any event, some of the subsidies lack consistency: for instance, subsidies are being given simultaneously for machinery that limits the intensity of soil tillage (such as zero-tillage drills) and machinery that increases the tillage intensity (such as rotavators). In fact, many subsidies in India have been counterproductive to zero tillage and actually have contributed to the sustainability concerns that undermine rice-wheat systems. For instance, subsidies for fertilizer, water, and rural electricity for irrigation undermine the incentives to rationalize the use of such resources and thus the attractiveness of resource-conserving technologies such as zero tillage. The widespread public intervention in produce chains with assured produce prices and marketing channels, particularly in India, also undermine incentives to diversify and rotate crops. Policy reforms to create an enabling environment for sustainable agriculture are likely to be more influential than the machinery subsidies. However, these imply addressing some of the more thorny policy issues such as the subsidy and taxation schemes that currently undermine the sustainability of rice-wheat systems (Erenstein and Laxmi 2008).

The success of zero tillage in India is based on the creation of viable, dynamic innovation systems, building on a successful and sustainable business model. Zero tillage is financially attractive to farmers and thereby has created farmer demand. Small-scale machine manufacturers see substantial market opportunities for their products, aided by the wide applicability of this mechanical innovation. They created a wide and competitive manufacturing base and played a key role in meeting the increasing demand. Tractor service providers have further enhanced technology access by making access to the zero-tillage drill divisible, thus allowing prospective zero-tillage drill owners to defer the investment decision.

Adoption surveys reveal that 60 percent of zero-tillage adopters in Haryana did not own a zero-tillage drill (Erenstein, Malik, and Singh 2007). Service providers have the added advantage of having hands-on experience and self-interest in promoting the technology (Erenstein and Laxmi 2008), although the use of a service provider increases farmers' dependence on third parties for the timely establishment of their wheat crop. So far, the business model has been somewhat less successful elsewhere in South Asia. In Pakistan, it has been hampered by more limited demand, a smaller manufacturing base, more expensive drills, and institutional controversy. In the Nepal terai, zero tillage has been hampered by political instability and the lack of a local manufacturing base, thus forcing the use of imported machinery from India, which implies additional transport costs and more problematic after-sale services. Tractor-based zero tillage has also largely bypassed Bangladesh, where farmers primarily use two-wheel tractors for their tillage operations. There are ongoing R&D efforts to adapt conservation agriculture-based machinery for two-wheel tractors in Bangladesh, somewhat hampered by the relatively undeveloped local manufacturing base. In the eastern plains there is also some limited use of manual surface seeding, which does not depend on agricultural machinery (Tripathi et al. 2006).

Zero tillage may also facilitate or induce other changes in the farming systems –in terms of diversification or intensification or both, for example (Erenstein and Laxmi 2008). Zero tillage also opens the way for a new service industry beyond the farm level – be it for machinery manufacturers or custom hiring services (Dixon et al. 2007). These system changes could generate substantial multipliers, although further studies are needed to substantiate their value (Erenstein and Laxmi 2008).

Environmental Sustainability

Zero tillage primarily has had positive effects on the environment in the Indo-Gangetic Plains (saving fossil fuel and water and reducing emissions of greenhouse gas), although further research is needed to substantiate and value these environmental impacts more rigorously (Akhtar 2006; Erenstein and Laxmi 2008; Hobbs and Govaerts 2009; Pathak 2009; Sarwar and Goheer 2007). The diesel savings are relatively robust– 36 liters of diesel per hectare, an 8 percent saving over conventional wheat tillage (Erenstein et al. 2008a; Erenstein and Laxmi 2008). Still, in spite of zero tillage's success in the Indo-Gangetic Plains, the full environmental benefits offered by conservation agriculture, including carbon sequestration, have yet to be fully utilized (Gupta and Sayre 2007; Laxmi, Erenstein, and Gupta 2007a). This is associated with the specific way zero tillage is applied to the rice-wheat systems in the Indo-Gangetic Plains, which distinguish it from related systems elsewhere (see, for example, Ekboir 2002; Erenstein 2002; Erenstein 2003).

Zero tillage is typically only applied to the wheat crop in the double-cropped system in the Indo-Gangetic Plains (Erenstein and Laxmi 2008). The use of zero tillage in wheat has limited spillovers to the productivity and management of the subsequent rice crop (Erenstein et al. 2007a; Erenstein et al. 2008a). For the rice crop, intensive and wet land preparation followed by transplantation still prevails. The reduction of tillage in rice-wheat systems has thus far been only partially successful, reflecting the increasing acceptance of zero tillage for wheat. Reducing tillage intensity for the subsequent rice crop still presents a challenge, particularly in terms of water and weed management and available germplasm (Erenstein 2007). Ongoing research (on-station and on-farm) in the Indo-Gangetic Plains is addressing these challenges and attempting to adapt viable "double no till" rice-wheat systems (Khan et al. 2009; Saharawat 2009; Singh, U. P. et al. 2009).

Zero-tillage wheat also does not necessarily imply the retention of crop residues as mulch in the Indo-Gangetic Plains. In fact, the prevailing zero-tillage seed drills are relatively poor in trash handling—but for better or worse, this has not been a major issue in view of the limited biomass remaining after the rice crop, once the prevailing residue management practices have been employed (Erenstein and Laxmi 2008). Leaving more crop residue as mulch implies the need for adaptation of zero-tillage drills. Ongoing R&D has already generated some second-generation zero-till seed drills that are able to handle significant residues, but their cost is still relatively high. Leaving more residue also implies the need to address potential trade-offs with existing residue uses (Erenstein et al. 2007b; Erenstein and Laxmi 2008).

In South Asia, crop residues are an integral part of rural livelihoods. Their utilization provides coherence to the prevailing smallholder crop-livestock systems (Devendra 2007; Erenstein et al. 2007b), being important sources of livestock feed for the dominant species in the region (cattle, buffalo, and goat) and sometimes having other productive uses such as fuel, construction material, and mulch. The relative importance of each use varies geographically and by crop and is associated with poverty incidence (Erenstein et al. 2007b; Parthasarathy Rao and Birthal 2008; Singh et al. 2007; Thorpe et al. 2007; Varma et al. 2007). The intensity of residue utilization as feed has an inverse association with farm size and a positive association with rural poverty in South Asia's Indo-Gangetic Plains (Erenstein 2009a).

The prevailing crop residue management practices in the Indo-Gangetic Plains are largely incompatible with residue retention as mulch, despite significant biomass production (Erenstein et al. 2007b). The ex situ use of crop residues as livestock feed is near universal and rigorous, whereas the increasing mechanization of rice and wheat harvesting practices has trade-offs in terms of residue use and management. Wheat is the traditional food crop in the northwest Indo-Gangetic Plains, and wheat residues are the corresponding basal feed for ruminant livestock. This implies significant imbalances in terms of seasonal residue extraction in the area, with surplus rice straw being burned in situ during land preparation (Bijay-Singh et al. 2008; Erenstein et al. 2007c; Gupta et al. 2004; Samra, Singh, and Kumar 2003). This is particularly so after combine harvesting of nonfragrant rice (74 percent of rice straw burnt according to farmers' estimations), compared to 22 percent burnt after manual rice harvesting, while in wheat, even after combine harvesting, only 10 percent is burnt (Teufel, Erenstein, and Samaddar 2008). Proceeding to the eastern plains, rice becomes the traditional food crop and rice straw the preferred basal feed. In the lower Gangetic plains, where manual harvesting still prevails, only an estimated 4 percent of the rice straw is burnt, whereas 62 percent is fed. In the same area, straw from the less widely cultivated wheat crop is primarily burnt (71 percent according to farmer estimates), either as household fuel or on the field (Teufel, Erenstein, and Samaddar 2008). The widespread use as feed implies that crop residues have significant value, and residue markets and institutional arrangements have developed accordingly. There are also significant regional variations in nonfeed residue uses like fuel and construction material. Such potential trade-offs need to be addressed by R&D and will present particular challenges for conservation agriculture-based technologies in the densely populated and poor eastern plains (Erenstein 2009a).

Retention of crop residues as soil cover is imperative in continuous no-tillage systems (Erenstein 2002; 2003). The widespread use of zero-tillage wheat without necessarily maintaining some soil cover in the Indo-Gangetic Plains has so far had limited perceivable negative consequences. This is, however, a consequence of the seasonal nature of zero-tillage use, with plots still being seasonally tilled for the subsequent rice crop. However, with a year-round —or double no-till— rice-wheat system, residue retention becomes imperative (Erenstein 2009a).

Zero-tillage wheat after rice in the Indo-Gangetic Plains does not necessarily entail an increased reliance on herbicides, reflecting that paddy rice fields are relatively weed free at harvest time (Erenstein and Laxmi 2008). In fact, by reducing soil movement, zero tillage serves as an effective control measure of *Phalaris minor*, a major weed that has reduced wheat yields in the area and that in the mid-1990s showed emerging resistance to isoproturon after continuous and widespread use of this herbicide during previous decades (Franke et al. 2003; Singh, Kirkwood, and Marshall 1999; Vincent and Quirke 2002; Yadav and Malik 2005). The ability to control herbicide-resistant *Phalaris* thereby became one of the drivers for adoption of zero tillage in northwest India, which in combination with new herbicides eventually managed to control the *Phalaris* problem.

Conservation agriculture is a wider concept than zero tillage and involves minimal disturbance of the soil, retention of residue mulch on the soil surface, and a rational use of crop rotations (FAO 2007; Harrington and Erenstein 2005; Hobbs 2007). The conservation agriculture principles—minimal soil disturbance, surface residue retention, and crop rotation—along with profitability at the farm level— are increasingly recognized as essential for sustainable agriculture. Alternatively, zero tillage alone is an insufficient condition for conservation agriculture (Erenstein et al. 2008b), and while attractive in the near term, may be unsustainable in the longer term (Erenstein et al. 2008b; Harrington and Erenstein 2005).

To enhance zero tillage's environmental sustainability there is a need to use zero tillage as a stepping stone to conservation agriculture and start addressing the remaining challenges (Erenstein 2009a). This includes the need for more crop rotation, although the combination of secure produce markets and irrigation-ensured yield stability makes rice and wheat production a low-risk venture that has proven difficult to displace so far. Still there is an increasing scope for diversifying rice-wheat systems, particularly in the northwest Indo-Gangetic Plains, be it in response to technological developments (Jat et al. 2006), rapidly evolving domestic markets (due to economic growth, urbanization, and emerging marketing chains), or the increasing water scarcity (Erenstein 2009a).

Social and Political Sustainability

Equity still poses a challenge to zero tillage's impact—both geographically and within rural communities. Zero-tillage wheat so far has primarily benefited the northwest Indo-Gangetic Plains (Laxmi, Erenstein, and Gupta 2007a), an area that typically has more intensive and productive rice-wheat systems, more favorable institutional support, and markedly less poverty than the eastern Indo-Gangetic Plains (Erenstein et al. 2007b). Rural development indicators in the Indian states of Punjab and Haryana now compare well with those of middle-income countries. Yet, large tracts of the Indo-Gangetic Plains remain mired in dire poverty, despite their agricultural potential. The main exponent of this is the poverty pocket of the eastern Indo-Gangetic Plains, an area with 500 million people, typically characterized by smallholders (70–90 percent of the farm households have less than 2 hectares) and widespread poverty 30 percent or more below the official poverty line, where more than two-thirds survive on less than US$2 per day) (Erenstein 2009a).

Although the early focus of R&D on zero tillage in the rice-wheat system is in part justified in view of the risks inherent in technology development, there is an increasing need to directly target poorer areas and poorer households (Erenstein 2007). In fact, the potential yield gains and cost savings associated with zero tillage are even more pronounced in the areas with less intensified agriculture such as the eastern Indo-Gangetic Plains, thereby potentially reducing poverty and regional inequality (Erenstein and Laxmi 2008). The initial R&D results in the eastern plains are encouraging but not well documented or widely published. Yet, most references to zero tillage and the rice-wheat systems in the Indo-Gangetic Plains are still based on or extrapolated from the intensive northwest situation. This risks ignoring the significant variations across the plains, both in biophysical terms (Narang and Virmani 2001) and socioeconomic indicators such as poverty and population density (Erenstein, Hellin, and Chandna 2007).

Resource-saving technologies developed for the capital abundant northwest Indo-Gangetic Plains are not necessarily appropriate for less capital- abundant regions of the eastern plains. The popularity of two-wheel tractors in Bangladesh and Nepal is a case in point—these being more appropriate for the small farms and plots and less capital-intensive than four-wheel tractors. There is thus a need for local adaptation instead of simply transferring "capital-biased" technologies, and initial results of such adaptations are encouraging (see, for example, Biggs et al. 2004; Hossain et al. 2006; Wohab et al. 2006).

Studies have reported the benefits of zero tillage to be relatively scale neutral with both large and small landholders adopting zero tillage (Erenstein and Laxmi 2008; Jamal, Akhtar, and Aune 2007). This is facilitated by the ability of smallholders to contract zero-tillage drill services, just as they do for their tillage services in general, which makes the tractor-based machinery divisible. Still, zero tillage tends to be adopted first by the better endowed farmers (Laxmi, Erenstein, and Gupta 2007a; Sarwar and Goheer 2007). Erenstein and Farooq (2009) indicate that zero-tillage adoption in the initial diffusion stage is strongly linked to the wealth of the farm household and rice-wheat specialization. The significant wheat area in zero tillage implies larger annual benefits, lower relative learning costs, and earlier payback to a zero-tillage drill investment. Studies in eastern Uttar Pradesh report that all socioeconomic farmer groups have benefited from using zero tillage, albeit the extent of use has been higher among the larger farmers (Jafry 2007; Joshi et al. 2007b). This is in part associated with differential access to information.

The differential adoption of zero tillage calls for a closer consideration of equity implications in future research and development. The structural differences between adoption categories also easily confound the assessment of the impact of zero tillage (Erenstein 2009b; Erenstein and Farooq 2009). Therefore, the accessibility of smallholders to zero-tillage knowledge merits particular attention, and alleviating knowledge blockages can further an equitable access to this promising technology (Erenstein and Farooq 2009). There is an important role here for agricultural service providers, particularly in view of the widespread reliance of zero-tillage adopters on contracted zero-tillage drill services.

Farm surveys have also revealed some discontinuation of zero tillage, and better understanding of the rationale for disadoption merits further scrutiny (Erenstein et al. 2007a). There was no clear single overarching constraint, but a combination of factors was at play, including technology performance, technology access, and seasonal constraints. The slower diffusion and higher disadoption in Pakistan Punjab are likely associated with the ongoing institutional controversy over zero tillage there. For instance, Iqbal et al. (2002) have highlighted that in Punjab "some government agencies … have differences of opinion on the usefulness and the benefits of zero tillage." This is also illustrated by Sheikh, Rehman, and Yates (2003), who find a significantly negative association between the number of extension visits and zero-tillage adoption, leading them to conclude that "[t]his suggests that extension workers are not recommending the technology." Provincial agricultural extension is indeed not supportive of zero-tillage wheat, and this message is carried through in their extension campaigns and by their field staff (Akhtar 2006; Jafry, Ahmad, and Poswal 2006). One of the fears is that by not plowing, zero tillage may encourage overwintering of the stem borer in the rice stubble, which may undermine the productivity and competitiveness of basmati rice, a major export crop. However, there is no scientific evidence of such risk (Inayatullah et al. 1989; Srivastava et al. 2005). Filling the institutional vacuum, On Farm Water Management (OFWM, Lahore) has played an important role in promoting this technology. This has created institutional rivalry between OFWM and agricultural extension, with unfortunate implications for the farmers and the technology alike in Punjab, particularly in view of conflicting information. In contrast, the initial reluctance of many stakeholders vis-à-vis zero tillage in India has been transformed into a significant support for zero tillage at various levels (Erenstein et al. 2007a).

In the Indo-Gangetic Plains, little has been documented about zero tillage's contribution to conflicts between stakeholders. In part, this may reflect a primarily technocentric approach and an inherent diversity among stakeholders that has often resulted in only partial analysis, if any (Erenstein 2007). Still, timely access to a zero-tillage drill is key to ensuring timely wheat establishment and thereby being able to reap the associated yield gains. Differential access to zero-tillage implements and knowledge may therefore have contributed to the differential yield performance of zero-tillage wheat in Pakistan Punjab, where zero tillage resulted in lower yields only on smallholder farms (Erenstein 2009b). Agricultural scientists have increasingly recognized the need to acknowledge differences in the resource base of their target group —although the boundary is often fuzzy between what is considered a large farmer and a smallholder. And, more worryingly, the implications for disadvantaged segments of society such as the landless in South Asia are often forgotten (Erenst1ein 2007).

Labor-saving technologies inherently shift income from laborers to producers. The mechanized land preparation that prevails in the Indo-Gangetic Plains, however, implies that the labor-savings associated with zero-tillage wheat are limited. Still, some stakeholders have raised concerns about the perceived labor displacement associated with zero tillage (Jafry 2007; Laxmi, Erenstein, and Gupta 2007a*)*. The concerns raised by migrant and landless laborers about the possible use of zero tillage for rice seem more grounded, as they fear a significant loss of earnings were rice no longer transplanted (Laxmi, Erenstein, and Gupta 2007). The gender segmentation in the labor market would impose further social costs (Singh et al. 2005). There would also be regional equity dimensions, as the intensive northwest systems still rely on migrant labor from the eastern plains to alleviate their labor peaks. This calls for a better understanding of livelihood implications and a broader stakeholder dialogue/participation in technology development (Erenstein 2007).

Recently, international commodity prices for oil, fertilizer, rice, and wheat first increased dramatically, contributing to a global food crisis in 2008, and then plunged during the subsequent financial crisis. These developments have only increased the relevance of resource-conserving technologies such as zero tillage. Zero tillage's ability to minimize tilling and fuel use is particularly attractive, alleviating production costs. Increasing concern about water productivity in agriculture also calls for water-saving technologies. Technologies based on conservation agriculture also help regulate the soil ecology (Erenstein 2002; Erenstein 2003; Jat et al. 2009), which is increasingly relevant as an adaptation strategy for climate change. Climate change will indeed exacerbate the heat stress at the end of the wheat season, thereby enhancing the potential payoff to zero tillage in terms of timeliness. At the same time, climate change raises serious questions about the future of rice-wheat systems and agriculture in the Indo-Gangetic Plains in general (Aggarwal et al. 2004; Grace, Jain, and Harrington 2002; Ortiz et al. 2008).

5. LESSONS LEARNED

Conservation agriculture-based technologies like zero tillage offer potentially high economic, environmental, and social gains in the Indo-Gangetic Plains, although actually realizing all these gains on the ground has proven challenging (Erenstein 2009a; Erenstein and Laxmi 2008). The vast majority of farmers in South Asia's Indo-Gangetic Plains have adopted zero tillage because it provides immediate, identifiable, and demonstrable economic benefits such as reductions in production costs and timely establishment of crops, resulting in improved crop yields. But in spite of the efficiency gains and the recent diffusion of zero tillage, most farmers, especially the small- and medium-scale farmers, have difficulty in following the wider basic tenets of conservation agriculture, particularly year-round tillage reduction, crop residue retention, and crop rotation. This implies the associated environmental benefits are yet to be fully realized. Equity has also posed a challenge so far, and there is a need to extend the gains to the less endowed areas and less endowed farmers.

Research and development thus still faces the challenge of adapting and developing sound, economic conservation agriculture practices that all types of farmers will adopt year round across crops and across regions. But the potential is there to build on the success of zero-tillage wheat and thus to use zero tillage and the associated efficiency gains as a stepping stone to conservation agriculture and equitable rural development. Still, zero tillage is no panacea, and complementary technologies that are privately and socially attractive are needed. At the same time, technological change can only go so far and needs to be complemented with institutional change to create the necessary incentives to induce change and to align private and social interests.

Despite the wealth of information on zero tillage in the Indo-Gangetic Plains, there still are significant knowledge gaps. Particularly scarce are reliable and empirically based zero-tillage diffusion indicators and documented evidence of zero tillage's socioeconomic, livelihood, and environmental impacts. Addressing these knowledge gaps would significantly enhance our understanding of the sustainability implications and remaining challenges. A better understanding of livelihood implications and stakeholder dialogue/participation would enhance the ability to keep interventions "pro-poor" and need-based. Addressing the knowledge gaps would also enhance our ability to scale-out and replicate the success in a cost-effective, equitable, and sustainable manner.

Keys to Enhancing the Impact of Zero Tillage

Zero tillage's impact in the Indo-Gangetic Plains was enabled by a number of key aspects inherent in the technology, the process, and the context. The technology itself proved attractive from a private viewpoint – both for technology suppliers and technology users. Without such profitability, the technology's initial public-sector, supply-led nature would not have transformed itself into private-sector supply and demand and viable delivery pathways and business models in India.

In creating this dynamic system of innovation, the intervention's process combined elements of persistence, flexibility, inclusiveness, and facilitation. Over time success was built on the concerted efforts of an array of stakeholders that spanned the public and private sectors and national and international research systems and included several persevering zero-tillage champions. The Rice-Wheat Consortium played a pivotal and innovative role as facilitator and information provider, technology-clearing house, and capacity builder. The Consortium helped provide both resources to get the technology out into farmers' fields and manufacturers' workshops and an active and dynamic platform for stakeholder interaction. The importance of these policy and institutional aspects in shaping impact pathways and enabling the system of innovation to be built around technologies based on conservation agriculture has been reported in South Asia and elsewhere (Ekboir2002; Erenstein et al. 2008b; Harrington and Erenstein 2005; Harrington and Hobbs 2009; Sims, Hobbs, and Gupta 2009).

The context provided a final key aspect. The slowdown in productivity growth in rice-wheat systems and concerns over production costs and sustainability opened up the door to resource-conserving technologies like zero tillage. Many farmers became interested in the prospect of enhancing their stagnating bottom line. Selected researchers were interested and excited by the prospect of enabling change in farmers' fields. Policymakers were interested in technological solutions to enhance the sustainability of South Asia's cereal bowl, while avoiding more demanding institutional changes.

The success story of zero tillage in Haryana combines many of these elements. The herbicide tolerance of the weed *Phalaris minor* was so severe that it helped in breaking through the enormous reluctance of farmers to even try zero-tillage technology. Key champions picked up the technology and promoted it despite initial resistance. The private sector made many improvements to the prototypes of the implements, based on interaction with and feedback from farmers. The innovation process thereby benefited from many "hinge of fate" moments where coincidence and personalities enabled progress (Harrington and Hobbs 2009).

Scaling out the Impact of Zero Tillage

Scaling-out strategies will need to build on the local context and stakeholders to establish a dynamic innovation system. Within the vast Indo-Gangetic Plains, strategies to expand zero tillage to new regions will thus differ between the more intensive northwestern plains and the eastern plains and between India and neighboring Pakistan, Nepal, and Bangladesh. More concerted efforts and resources are needed to strengthen the R&D in these neighboring countries and in the eastern plains. The experience in Pakistan highlights the importance of bringing on board all relevant stakeholders, including policymakers and extension workers. More research is particularly needed to create year-round zero-tillage (double no-till) options for rice-wheat systems and to understand and address environmental and social issues.

The zero-tillage experience in the Indo-Gangetic Plains provides a number of useful guidelines for future efforts to replicate it elsewhere. The key to success is having a financially attractive intervention. No matter how attractive an intervention is from the environmental or social point of view, without the private interest to stimulate demand and supply it will not fly. The development of viable and dynamic innovation systems that can deliver and adapt interventions such as zero-tillage drills will be essential to replicate and extend the success that has been realized in reducing tillage for wheat.

Agricultural scientists and development practitioners therefore need to move away from linear processes to more participatory interventions. Experts often have strong convictions about proposed interventions and what is best for the system. Yet the key to change is creating the demand and enabling it to transform the system. Sowing the seeds for a successful business model is critical. Showing that the technology can deliver its promise in the farmers' villages and fields is critical and that it can be actively facilitated through on-farm adaptive and participatory R&D work and encouraging farmer-to-farmer exchanges and extension through traveling seminars. Another critical aspect is to link famers with knowledgeable, accessible, and responsive yet self-interested technology suppliers. This includes a local manufacturer who can make equipment that will do the job well at a competitive price and adapt and repair it as needed. Successful business models are also more likely to emerge when the intervention target area and populations are substantial instead of minor niches – the wide applicability of zero-tillage drills across the Indo-Gangetic Plains being a case in point. Moving agricultural experts away from the yield paradigm is another challenge. Indeed, producing the same with less can still be a very attractive proposition for enhancing the farmers' bottom line, but it implies a shift in the mindset that has traditionally focused on producing more per unit of area.

A final guideline for scaling out similar agricultural interventions is to start with reaping the easy gains or low hanging fruits. Such a phased approach generates the necessary successes and momentum that will help address second-generation problems. Such an approach will likely be more successful than tackling environmental or social issues head on. But this does not imply that one can simply ignore the more challenging longer-term and equity issues. In fact, from the onset, one should emphasize the more compatible interventions that can serve as a stepping stone toward sustainable conservation agriculture. This serves as a salutary reminder that farmers have an outstanding ability to adopt the components of proposed technological packages that best fit their needs and interests. One should also emphasize equitable access from the start – be it in terms of inclusiveness of less endowed areas and households and ensuring appropriateness of interventions. Therefore the challenge remains how to minimize the trade-offs with environmental and social goals in our enduring quest for immediate successes.

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