Johansen, C., Haque, M.E., Bell, R.W., Thierfelder, C. and Esdaile, R.J. (2012) Conservation agriculture for small holder rainfed farming: Opportunities and constraints of new mechanized seeding systems. Field Crops Research, 132 . pp. 18-32.

Conservation agriculture for small holder rainfed farming: Opportunities and constraints of new mechanized seeding systems

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Abstract

Small holder farmers in rainfed agriculture believe that soil tillage is needed to maximize crop yields. However, as cropping intensity, and hence tillage intensity, increases there may be a decline in particular physical, chemical and biological properties of the soil which limit crop yield. This is primarily caused by declining soil organic matter, its oxidation being accelerated by tillage, particularly in warmer climates, and exacerbated by the limited return of above-ground biomass to the soil due to its competing use for other purposes. In large-scale commercial agriculture declining soil quality has been effectively addressed by conservation agriculture—cropping systems based on minimum tillage, crop residue retention and appropriate crop rotations and associations, preferably including legumes. This has required development of minimum tillage planting equipment along with herbicide technology to achieve weed control that is traditionally achieved through tillage. However, a shortage of mechanized options suitable for small holder farmers is creating an impediment to the adoption of conservation agriculture practices that would arrest the decline in soil quality in their fields. In South Asia, two-wheel tractors are replacing animal-drawn ploughing in small holder plots. This speeds the tillage operation and hence the turnaround time between crops, which may increase opportunities for crop intensification, but the problems associated with full tillage remain. Over the previous decade planter attachments to two-wheel tractors have been developed which permit seed and fertilizer placement with minimum to zero tillage in a single-pass. Recent tests have demonstrated that use of these implements can produce crop yields equal to or better than conventional tillage involving hand broadcasting of seed and fertilizer. Further, fuel and labour costs, seed and fertilizer inputs and turnaround time between crops can be reduced. In Africa, the introduction of animal-drawn rippers and direct seeders, originally developed for small-scale farmers in Brazil, is considered as a major breakthrough to small-scale farmer mechanization. It significantly reduces labour required for planting and benefits may be even greater if herbicides can be effectively used for weed control. Nevertheless, movement towards minimum tillage with two-wheel tractor mounted planters and animal-drawn direct seeding equipment is constrained by weed management issues. There are problems of availability and of safe and effective use of herbicides by resource-poor farmers and there is a need to develop more integrated weed management strategies that can be combined with small-scale planters. There is also a need to optimize the performance of small-scale planters to suit farmers' needs in different agro-ecological environments. Tools and concepts are now available to implement conservation agriculture for small holders and thereby increase profitability of their cropping practices and at the same time improve soil quality and sustainability of their livelihoods. However, much more adaptive research and on-farm evaluation is needed across a diverse range of soils, cropping systems and agro-ecological regions to bring conservation agriculture to more small holders.

Keywords: Animal traction direct seeder; Crop rotation; Jab-planter; Minimum tillage; Mulching; Ripper tines; Seed drills; Soil organic matter; Strip tillage; Two-wheel tractors; Weed management; Zero tillage

Introduction

Most crop production in Asia, Africa and Latin America is based on subsistence agriculture implemented by resource-poor small holder farmers. This form of agriculture is characterized by limited application of inputs, distorted markets, deteriorating soil conditions, and now increasingly uncertain weather patterns (Christensen et al., 2007). The factors leading to soil degradation over time include limited organic matter returns to the soils, minimal and unbalanced fertilizer addition, limited options for crop rotation and the perceived need for regular tillage. Small holder farmers generally try to maximize tillage, within their constraints of time, labour and available implements, primarily for the purpose of weed management and to create a seed bed with a fine soil tilth suitable for germination and seedling establishment. Additional reasons for small holder farmers to practice conventional tillage, by manual, animal powered or mechanized means, include mineralization of nutrients, incorporation of fertilizers, crop residues and soil amendments, temporary alleviation of compaction, and management of some soil-borne diseases and insects (Hobbs et al., 2008 and Kassam et al., 2009). However, regular tillage breaks down soil organic matter through mineralization, more so in warmer climates (Kirschbaum, 1995), thus contributing to deteriorating soil physical, chemical and biological properties (Wall, 2007). The physical effects of tillage also adversely affect soil structure, with consequences for water infiltration and soil erosion through runoff, and create hardpans below the plough layer (Thierfelder and Wall, 2009). These adverse effects of tillage have been addressed over recent decades by the development of conservation agriculture (CA) (Garcia-Torres et al., 2003). CA is defined as cropping systems based on minimal soil disturbance, permanent surface cover through crop residue retention and diverse crop rotations and associations (Hobbs et al., 2008 and Kassam et al., 2009). Most progress in CA has been made in large-scale commercial agriculture where powerful tractors are available to pull minimum tillage seeding equipment and herbicides are routinely used for weed control. Derpsch et al. (2010) estimated that 111 million ha would be cropped using the principles of CA but that this was mainly under commercial farming systems in the Americas and Australia. CA has received increasing attention by the commercial farming sector as it drastically reduces fuel costs, reduces the drudgery and labour requirement of multiple tillage operations, and minimizes machinery wear and tear (Raper et al., 1994 and Thomas et al., 2007).

Small holder farmers primarily reliant on rainfall rather than irrigated systems have generally not adopted CA practices yet, for various reasons—lack of knowledge about CA and how it could potentially improve their own agriculture, the perceived complexity of this new cropping system, unavailability of appropriate minimum tillage implements, limited access to herbicides, and the change of mind set required to shift from the habits of multiple tillage to minimum tillage (Wall, 2007). However, opportunities are opening up to make it easier for small holder farmers to change from excessive tillage to various forms of minimum tillage. There are options using hand or animal-drawn implements (Thierfelder and Wall, 2010) and increasingly for planters mounted on two-wheel tractors. In the last two decades numbers of two-wheel tractors (Haque et al., 2004) and shallow-tillage single-pass planters have rapidly expanded in Asia (Miah Monayem et al., 2010). These were primarily designed for rotary tillage, which can even exacerbate the problems of soil tillage. Over the recent decade, however, there have been innovations made to both two-wheel tractor as well as animal-drawn direct seeding implements that do permit adequate seeding into minimally disturbed soil. This provides a window of opportunity to introduce CA among small holder farmers, not only in terms of reduced soil disturbance but also with respect to biomass cover and crop rotation. Effective CA practices for small holders would also enable them to capture the economic benefits already enjoyed by the large-scale users of CA, reduced fuel and labour costs and improved timeliness of operations.

However, there are many biophysical and socio-economic constraints to small holder farmers in adopting CA (Giller et al., 2009) and it will be necessary to develop effective strategies to transfer the emerging technologies to them. It is noted that CA in many areas evolved through innovation networks linking farmers, extension personnel, researchers, engineers/mechanics, input suppliers, and credit providers (Ekboir, 2002, Pieri et al., 2002, Thomas et al., 2007 and Hobbs et al., 2008). Such a collaborative approach would also seem necessary in bringing CA to small holder farmers, but with modifications tailored to the limited resources available to them. This review examines recent innovations in minimum tillage implements suitable and adaptable for small holder agriculture. It also discusses how these could catalyze widespread adoption of CA practices in resource-poor environments, and suggests possible pathways to adoption.

Tillage and small holder farming

Characteristics of small holder agriculture in Asia and Africa

This review focusses on small holder agriculture in South and South-East Asia, China and southern Africa drawing from the authors' particular experience in these regions. It is recognized that many innovations in CA, in both commercialized and small holder farming, have occurred in South America, but we only draw on that information as it relates to our focus area. We define small holder agriculture as that conducted by farmers using predominantly family labour and for whom the farm provides their main source of income and livelihood. Small holder farm size is considered to be that less than 3 ha, even though fields farmed by a household may be dispersed around a village. In many cases in Asia and Sub-Saharan Africa small holder farmers are also subsistence farmers, in that they use few if any purchased inputs, the main output of their farming activities is consumed directly, and only a minor proportion of their farm output is marketed. As for farming everywhere, small holders have to manage risks associated with their environment and socioeconomics, but have less room to manoeuvre than in well-endowed farming systems. The soils they farm are often marginal and degrading (Lal, 2000) and they face predictable and unpredictable pest and disease problems about which they can do little. Most small holder farms are exposed to erratic rainfall patterns. However, in some regions, such as the Indo-Gangetic Plains (IGP) of South Asia, many small holders do have access to irrigation. Nevertheless, this often does not solve their soil moisture constraints due to difficulties of timely access to the irrigation water needed (e.g. erratic availability of electricity or fuel for pumping) and sub-optimal irrigation practices. This review mainly addresses CA for rainfed small holder agriculture, where sub-optimal soil moisture is a common constraint to crop performance, but also covers situations where irrigation is available. Small holder farmers are also characterized by limited state-of-the-art knowledge on technical aspects of their farming enterprise, minimal capital or credit to purchase inputs, and distorted markets. To supplement income for basic household needs various family members sometimes need to undertake off-farm employment or hunting and gathering in nearby areas of natural vegetation. These circumstances in themselves pose challenges to the introduction of CA practices, particularly if it is to rely on mechanization.

Tillage effects on soil quality

While thorough tillage of the soil has immediate advantages for controlling weeds and creation of a fine soil tilth for sowing seed and for seedling emergence, there are adverse consequences of regular tillage on soil quality which become more apparent over the longer term. Soil quality is largely determined by soil organic matter (SOM) status and there is much accumulated evidence in temperate and tropical soils of declining SOM with tillage as compared to relatively undisturbed soil (Ogle et al., 2005). There is a range of soil physical, chemical and biological consequences to declining SOM caused by tillage. A decline in SOM reduces soil particle aggregation (Chaney and Swift, 1984), which slows water infiltration (Thierfelder and Wall, 2010), reduces aeration and increases bulk density, thereby restricting root distribution and function. With reduced SOM, soil water holding capacity is decreased and susceptibility to water erosion increased through increased runoff (Thierfelder and Wall, 2010). Declining SOM also diminishes the ability of the soil to release nutrients in approximate synchrony with crop demand (Drinkwater and Snapp, 2007). SOM provides exchange sites for nutrient ions, minimizing their leaching or sorption on clay minerals, but increases their availability for plant uptake through slow release to the soil solution. SOM also hosts the microorganisms which facilitate nutrient cycling, as well as encouraging soil fauna such as earthworms, which further improve soil physical properties such as water infiltration through the channels they form. A decline in SOM results in an inevitable decline in soil biological activity (Soon and Arshad, 2005).

Tillage and economic efficiency

To achieve a net increase in economic efficiency with minimum tillage or zero tillage compared to conventional tillage the perceived benefits of traditional tillage practices have to be offset. To induce a change from conventional to minimum or zero tillage, clear economic benefits must be apparent, for small holder as well as better endowed farmers. A first requirement is that there is no substantial reduction in crop yield or increased risk of growing that crop. As a consequence of reduced input requirement for minimum tillage there are opportunities for reduced fuel costs, lower labour requirements, and improved timeliness of farm operations, factors that could considerably enhance profitability of the cropping operation. These are discussed more fully in Section 3.

Depending on soil type, frequent tillage may cause the development of a hardpan at the bottom of the ploughed or hoe cultivated layer which can impede water infiltration and root penetration (Thierfelder and Wall, 2009). Irrespective of SOM, tillage damages soil structure, and hence soil water holding and release characteristics, through physical disruption of soil aggregates (Beare et al., 1994). Furthermore, when there is limited soil surface moisture at seeding, tillage may increase evaporation from the soil surface, exposing seedlings to water stress.

Evolution of conservation agriculture

Large-scale commercial farming

Although the universally accepted practice of tillage was queried in the 1940s (Faulkner, 1943), the practical application of minimum tillage on a large scale did not occur until two decades later. This was prompted by increasing concerns of soil erosion exacerbated by traditional practices of regular and thorough tillage (Thomas et al., 2007). It became feasible by the development of low-cost herbicides such as Roundup® containing the active ingredient glyphosate (N-(phosphono-methyl) glycine) manufactured by Monsanto in 1974 (Baker and Saxton, 2007b). With the advent of chemical weed management one of the reasons for tillage became redundant. Experimentation with minimum tillage began in North America and the UK because this is where herbicides first became widely available. It then spread to commercial farming in South America and Australia, particularly targeted to large land holdings offering economies of scale in reducing tillage requirements. If tillage was to be minimized or foregone it became necessary to develop implements for effective placement of seed and fertilizer into undisturbed soils; these required more robust tine and disc systems. This was done for the increasingly powerful tractors becoming available from the 1960s, especially considering the additional traction requirements necessitated by seed and fertilizer delivery into undisturbed soil. The research and development process encouraged, and indeed resulted in, close interaction between researchers, engineers, mechanics and farmers due to the multiplicity of differing requirements of soils and cropping systems and the need for ongoing trial and error modification of delivery systems. With development of techniques of chemical weed management and effective seed and fertilizer delivery systems with minimal soil disturbance, the other aspects of CA, increased soil coverage with crop residue or cover crops and more diverse crop rotations, became more feasible.

In southern Africa, no-tillage direct seeding systems appeared in the mid-1980s when specific machinery design and manufacturing started for the commercial farming sector. The main trigger for increased interest in direct seeding technologies in the region was large-scale soil degradation and fuel shortages, which increased the need for planting systems with a lower energy requirement. By 1998, it was estimated that about 30% of the commercial farmers in Zimbabwe had adopted CA (Nyagumbo, 1998). However, the spread of CA in large-scale commercial farming was based on high power traction, well beyond the means of most small holder farmers. Thus alternative pathways for introduction of CA among small holder farmers were required. Interestingly some of the Zimbabwean prototypes were later exported to India and Bangladesh were local manufacturers adapted them to small-scale farmer's conditions.

Benefits of minimum tillage based on experience in large-scale commercial agriculture, irrespective of the degree of crop residue retention and extent of crop rotation, are summarized in Table 1. Full implementation of the principles of CA involves a radical change in many farm operations. A new knowledge base is needed by farmers to establish crops, manage weeds, manage crop residues, respond to newly emerging diseases and insect pests, and manage diverse crops. Clearly, farmers who make the change are driven by an expectation of substantial benefits. These generally are the promise of cost or labour savings or productivity increases (Pieri et al., 2002).

Adjusting conservation agriculture for small holders

Conservation agriculture machinery design and development for small holder farmers was initially driven by Brazilian farmers, who have witnessed a revolution in CA equipment development and manufacture over the past 50 years. The major drivers for change in Brazil since the 1960s were the damaging side effects of conventional tillage-based agriculture leading to widespread soil erosion and degradation. It was estimated that 10 t of soil was being lost for every tonne of grain produced (Derpsch et al., 1991). Although many efforts initially focussed on the large-scale commercial farms there have also been initiatives to develop machinery for small-scale farmers interested in practicing CA especially in the States of Parana, Santa Catarina and Rio Grande do Sul. Currently, there is an estimated 200,000 ha managed by small-scale farmers under CA in Brazil (Wall, 2007). Machinery systems for small-scale farmers were mainly focussed on manual and animal traction seeding systems such as the manual jab-planter and animal traction direct planters. The Brazilian machines had spillover effects to southern Africa where new machinery is now developed and tested.

By contrast with development in Brazil, in southern Africa farmers were not the main driver for change to CA but donor-driven initiatives. In Zimbabwe, a GTZ/BMZ funded project on “conservation tillage” (CONTILL) operated from 1988 to 1998 (Hagmann, 1998). The major focus of this project was developing and extending small-scale farmer CA systems like mulch ripping and other resource-conserving seeding systems. However, the approaches were mainly developed on research stations with little farmer interaction. Therefore the adoption of new CA systems was generally limited. In Zambia, a World Bank funded project initiated the large-scale extension of CA in 1996 based on manually dug planting basins and later rip-line seeding systems (Haggblade and Tembo, 2003). However, CA started to really expand in southern Africa only in 2004, through several parallel developments. Various donors including DFID, GTZ/BMZ, FAO, SIDA, NORAD started initiatives in Zambia, Malawi, Mozambique and Zimbabwe promoting manual planting basins, jab-planters, ripper tine and animal traction seeding systems. Although these initiatives were donor-driven projects they involved more farmers after lessons had been learned from previous projects. In some areas, local innovation with CA strengthened interaction between farmers, researchers, machinery manufacturers, input suppliers, credit providers and many other players. The following sections examine recent developments on manual and animal-drawn CA planting systems, mainly from experience in southern Africa, and tractor-powered systems, mainly developed in South Asia.

Manual CA planting systems

There are basically three different manual CA systems being used in southern Africa.

Dibble stick

Farmers in Malawi practice CA with a dibble stick, a pointed stick that opens a small hole for planting (Fig. 1). If both seed and fertilizer is used the operator can create two holes for placement of each input. Farmers in Malawi currently prefer this technique over more sophisticated implements like the jab-planter because it follows traditional planting methods (i.e. planting the seed on ridges).

Planting basins

The second widely promoted CA system is based on manual dug planting basins (Fig. 2), a system originally developed by the Zimbabwean commercial farmer Brian Oldrieve. The basins are dug throughout the winter period with hoes to spread the labour for digging. At the onset of the rainy season they can be planted without time delays. There are various basin sizes promoted; in Zambia they are slightly bigger (40 cm × 15 cm × 18 cm) than in Zimbabwe (15 cm × 15 cm × 15 cm). Basins are excellent precision planting systems, which support many other good agricultural management practices like timely planting or precision application of manure and fertilizers. However, the creation of planting basins is still fairly labour intensive so that the system is mainly targeted towards manual, resource-constrained farmers without animal traction.

Jab-planters

The third seeding system is based on mechanical jab-planters (Fig. 3) originally developed by Brazilian manufacturers such as Fitarelli Machinas.[1] They were first imported to Zimbabwe and Mozambique in the early 2000s and various attempts were made to produce them locally. The jab-planter has two compartments, one for fertilizer and one for seed, and both are mounted on a wooden frame with two tips. Once the tips are pushed into the soil and opened by the operator seed and fertilizers drop into the planting hole. The machine can seed very effectively into mulch-covered no-tilled soil but has disadvantages, such as clogging of the tips if the soil is too sticky.

Animal traction systems

Ripper tine systems

The first ripper tine systems emerged in the late 1990s in Zambia and Zimbabwe and were mainly developed at the Magoye and Palabana Research Stations in Zambia. The Magoye ripper is a simple ripper attachment to the plough beam, which can be easily mounted after removing the shear blade of the animal traction mouldboard plough (Fig. 4). The operator creates about 10 cm deep rip-lines with the tool, which is pulled by a pair of oxen. The width can be adjusted with the type of wings attached. The Palabana subsoiler works down to 25 cm soil depth and can remove hardpans formed by previous cultivation and create a rip-line at the same time. Both systems are ideal transitional steps from plough-based systems towards animal traction direct seeding. The ripper attachment costs about US$ 25, a price that a small-scale farmer in possession of a pair of oxen can afford. The disadvantage of Rip-line seeding systems is seeding into residue-covered soils because the implement does not have a cutting disc (coulter) that can cut through residue. Another disadvantage is that seeding, fertilization and covering has to be done manually, which increases the overall labour requirements.

Direct seeding systems

In 2004, the first animal traction direct planters were brought into Zimbabwe by CIMMYT (International Maize and Wheat Improvement Center), which marked a milestone in small holder mechanization in southern Africa. The equipment originally developed by Brazilians (i.e. Fitarelli Machinas) was tested in the region in various target communities under different physiographic and agro-ecological conditions. The direct planter has a coulter, which cuts into mulch, a ripper tine that opens a small rip-line, a seed and fertilizer hopper and finally a drive wheel that activates seed and fertilizer release and covers the seed at the same time (Fig. 5). Fitarelli planters have seed plates for maize (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench) and beans (*Phaseolus vulgaris*L.), but other crops such as sunflower (*Helianthus annuus* L.) and cowpeas (*Vigna unguiculata* (L.) Walp.) can also be sown.

Although local machinery manufacturers were initially skeptical about these new machines local production has started and advanced prototypes with inclined seed plates are now available. Grownet Investments, a small machinery manufacturer from Zimbabwe, has developed an animal traction direct planter that is able to seed groundnuts (*Arachis hypogaea* L.), a crop that cannot be seeded even with the Fitarelli direct planter. The animal traction direct planter is a precision instrument and farmers are enthusiastic about operating this new equipment. It can seed 2 ha or more in one day depending on the availability of trained oxen. The main disadvantage at present is the price for the implement, which ranges between US$ 500 and 600 depending on the types of seed plates a farmer needs. It is expected that increased local production and farmer demand will reduce the price of these implements over time.

CA planters for two-wheel tractors

Although two-wheel tractors are popular with small holder farmers worldwide, the research community has until recently largely neglected them as traction units for CA cultural operations. This is mainly because of their limited tractive ability and thus the necessity that they be fitted with simple lightweight implements.

Single-pass shallow-tillage planter

Reduced tillage planting of crops using two-wheel tractors in Bangladesh was started in 1995 with the importation of the Chinese-made 2BG-6A seeder, which was subsequently named Power Tiller

Operated Seeder (PTOS), and, more recently, single-pass shallow-tillage planter (SPSTP). This seeder accomplished three operations in a single-pass—shallow tillage (to 60 mm), placement of seed in a furrow and levelling (Miah Monayem et al., 2010). The SPSTP is 1200 mm wide allowing it to plant up to six rows of a crop at 200 mm row spacing. It provides full rotary tillage and covers 0.14–0.20 ha h^{-1}. It uses a fluted-type seed metering system, but has no fertilizer application system.

Initially, the SPSTP was demonstrated to farmers through service providers in many areas of Bangladesh under a loan programme of CIMMYT (Roy et al., 2004). Compared with traditional broadcast sowing with tillage by a two-wheel tractor, Wohab et al. (2007)reported that the SPSTP required only about half as much time and fuel for sowing of wheat (*Triticum aestivum* L.) and jute (*Corchorus capsularis* L.). At an initial stage efforts were taken to fabricate the SPSTP locally, but the manufacturers are unable to maintain quality of the product at a standard comparable with the imported one. However, due to demand and increasing capacity of the local manufactures, several have started commercial manufacturing and marketing. At present, more than 1000 units of SPSTP are being used in Bangladesh (Fig. 6). The current (mid 2011) market price of the SPSTP imported from China is US$ 650 per unit.

The SPSTP should be considered a reduced tillage planter rather than a minimum tillage planter, as the one pass does involve considerable disturbance of surface soil. This, together with shallow placement of seed, renders germinating seed and emerging seedlings prone to moisture deficit when surface soil moisture is marginal or rapidly evaporating. Thus the SPSTP is better suited to irrigated than rainfed situations, where optimum surface soil moisture can be assured. Subsequent developments of planters for two-wheel tractors have concentrated on planting into soils with sub-optimal soil moisture involving minimal soil disturbance and greater depth control of seed and fertilizer placement.

Strip tillage

By setting rotary blades only directly in front of the furrow openers the SPSTP could be reconfigured as a strip tillage planter (Justice et al., 2003, Justice et al., 2004, Roy et al., 2004 and Roy et al., 2009).

The rotating blades also displace the stubble in front of the furrow openers. Although original strip tillage units cultivate up to 50% of the soil surface (Justice et al., 2003), the angle of the rotary blades and furrow openers can be reduced to minimize the width of the strip tillage slit. CIMMYT initiated development of a two-wheel tractor based strip tillage planter in 2001 using a Chinese 2BG-6A seeder to plant seed on new beds and permanent beds with strip tillage. A research team comprising Bangladesh Agricultural Research Institute (BARI), CIMMYT Bangladesh, and Agricultural Implements Research Centre (AIRC) of Nepal adapted the strip tillage configuration to South Asian conditions (Hossain et al., 2005).

Zero tillage

In Bangladesh, a Bolivian animal-drawn drill was converted for operation on a two-wheel tractor, by mounting it on a toolbar frame (Fig. 7). The development and testing of the prototype of this zero tillage planter was carried out in 180 farmers' fields during 1999–2004 (Haque et al., 2004). The effective field coverage of the planter was 0.18 ha h^{-1}, reducing planting cost of wheat by up to 83%. Turnaround time between harvest of rainy season rice and sowing of the winter season crop was reduced by 10–15 days compared to traditional crop establishment systems.

Bed planter

Minimum tillage planting can also be accomplished on permanent beds. While the initial bed forming involves major soil disturbance, once established the regular reshaping of beds involves only minimal soil disturbance. A two-wheel tractor operated and toolbar-mounted bed planter was developed at CIMMYT, Mexico in 2002 for making new beds and reshaping permanent beds to establish crops (K. Sayre, personal communication). This was modified for Bangladesh conditions (Hossain et al., 2004) to eventually evolve a unit that could make and shape beds and place seed and fertilizer in furrows on the bed in one pass (Wohab et al., 2009). Beds 60 cm wide are produced which can accommodate two rows of most of the commonly grown crops in Bangladesh.

Recent developments with two-wheel tractor seed drills

Since 2006, improved configurations for both zero and strip tillage were made in Bangladesh (Hossain et al., 2009a and Hossain et al., 2009b). Innovations in design include replacement of the roller with adjustable press wheels, placement of separate seed and fertilizer boxes above the handle bars, more robust and effectively designed furrow openers and an adjustable tool bar frame for attaching tines (Fig. 8). Various soil engaging options are available including tines, single disc openers, double disc openers and cutting coulters (Fig. 9). The zero tillage planter, with all rotor blades removed, could pull up to four tines in soft soils, but in drying clay soils, a 12 HP two-wheel tractor could pull only two tines but with excessive wheel slippage and variable seed placement (Hossain et al., 2009a). Use of press wheels with this planter enabled increased plant stand by 22, 17, and 25%, respectively, for wheat, maize and mung bean (*Vigna radiata*(L.) R. Wilczek) crops (Hossain et al., 2009a). For strip tillage, rotor blades are only left in front of the tines, which can be constructed from light weight materials (Fig. 10).

Despite these promising developments, none of these planters for two-wheel tractors are capable of readily changing between all modes of tillage—single-pass shallow tillage, strip tillage, zero tillage, bed planting and conventional rotary tillage. In South Asia, cropping intensity is high—for example, in Bangladesh each field on average grows 1.85 crops per year (BBS, 2005) and many fields grow three different crops in a year. Over a five-year cycle, due mainly to changing profitability of crops, 4–6 different crops with diverse seed sizes, seed rate, row spacing, fertilizer rates, seed depth, etc. may be cultivated. Hence a planter suited to such diverse cropping systems needs to have multi-functional capabilities. In these intensive cropping systems it is considered that potential purchasers of a minimum tillage planter for two-wheel tractors would require it to be: capable of successfully sowing many crops and operating year-round; cheap enough for service providers to purchase [of the order of Tk 40,000 (approximately US$ 570) in Bangladesh] or repay a loan within a few years; flexible for set up in the field with capability to quickly interchange between different tillage methods, seed rates, fertilizer rates, row spacings, seed size, planting depth; durable through use of good quality products and metals, and; light weight with minimal vibration. The Versatile Multi-crop Planter

(VMP) has been developed with this in mind (Fig. 11; Haque et al., 2010, Haque et al., 2011 and Islam et al., 2010). It is capable of applying seed and fertilizer in rows for: (a) single-pass shallow tillage; (b) strip tillage of varying width and depth of strips; (c) zero tillage; (d) bed planting for single-pass new bed making or reshaping of permanent beds with simultaneous planting and fertilizer application, and; (e) traditional full tillage following broadcast seeding.

The VMP permits seeding and fertilizing in four adjustable lines if row spacing is 200 mm while in the case of maize sown in 600–700 mm beds only one row per pass is sown. Unlike any other two-wheel tractor based planter, the VMP has a square rotary shaft and attachable brackets to clamp onto the shaft by two bolts. This permits rapid adjustment between tillage modes and row spacings in the field, using an Allen key, within 15–20 min. With the VMP, either a fluted roller for continuous seeding or vertical plate seed meters can be fitted depending on the precision required for seed placement. Seed sizes ranging from 2 to 160 g per 1000 seeds can be sown with the VMP. Significant improvements were observed with the VMP for emergence of chickpea (*Cicer arietinum*L.), lentil (*Lens culinaris* Medik.), mung bean, wheat, jute, black gram (*Vigna mungo* (L.) Hepper), rice (*Oryza sativa* L.), mustard (*Brassica campestris* L. var. toria.), etc. compared to conventional tillage with broadcast sowing.

Some Brazilian and Argentinean farm implement companies also manufacture two-wheel tractor seed drills. These units typically plant either one or two rows of crop. The soil engaging components consist of a coulter/tine combination, with an additional double disc opener to place the fertilizer. Seed metering is by a horizontal plate metering system, and a fertilizer attachment is available. Enterprising farmers and researchers have also adapted Brazilian made animal-drawn seed drills for use behind two-wheel tractors. The drills used to date have generally been of a double disc configuration for the soil engaging components. Although these South American seed drills are agronomically suitable for many conservation farming systems, use of disc drills is problematic for small holder farmers due to high initial capital cost and high maintenance factors. Disc openers are also unsuitable for hard setting and/or wet soils.

Research and development is continuing with the prospect of developing other implements for two-wheel tractors. Experimental coulter/tine combinations and double disc openers for the tine type toolbar mounted seed drill have been fabricated but are yet to be thoroughly field tested. Other implements being considered include: inter-row cultivator, boom spray, lister/furrower, grader blade, laser land leveller, mechanical implement lift system, and angled single disc opener (Thomas, 2009). Commercial production of these seed drills for two-wheel tractors has begun in Bangladesh and China, and other Asian manufacturers are showing interest.

Evaluation and uptake of recent models

Strip tillage with a two-wheel tractor in Bangladesh has been shown to decrease fuel costs by up to 82% and the land preparation costs by the equivalent of US$ 31 ha^{-1} (Tk 2120 ha^{-1}), compared to conventional, multiple-pass tillage (Haque et al., 2011). This value is comparable to or even better than other studies on fuel saving using the SPSTP (Hossain et al., 2005). These savings assume ever increasing importance in view of the continually increasing costs of fuel in Asia, and globally. The field coverage of 0.07 ha $h^{-1}$for strip tillage with VMP was comparable to rates obtained with the SPSTP (Hossain et al., 2005). Hence in a single day's operation about 1–1.5 ha can be planted by the VMP in either strip tillage or SPSTP modes. In Bangladesh, where typical field sizes are 0.1–0.2 ha, this is equivalent to 10–15 fields. The decrease in fuel cost lowers costs of crop production and increases profitability for farmers by 6 to 100%, depending on the grain price and yield. Based on adoption of minimum tillage planters by 10% of the 350,000 two-wheel tractor operators in Bangladesh, and planting of 20 ha per machine per annum, savings in fuel consumption could total US$ 21.8 million $annum^{-1}$.

A 30% labour savings was also achieved in strip tillage by a VMP mounted on a two-wheel tractor compared to conventional tillage with a two-wheel tractor, which could substantially increase crop profit (Haque et al., 2011). The decrease in labour requirements is particularly significant at critical times such as harvesting of rice when the opportunity cost of labour is high. Overcoming labour constraints at critical times enables small holder farmers to carry out timely crop operations, which leads to increased yield.

Experience in Punjab, India of mechanizing tillage (with four-wheel tractors) has shown that the labour saved moves from laborious to more sophisticated rural jobs as well as to new jobs and opportunities created. One of the spin-offs from mechanization and the development of planters for two-wheel tractors in Bangladesh has been the emergence of small agricultural contractors who hire out the two-wheel tractors and planters for tillage and crop establishment on a fee-for-service basis. The average rate of return on investment by hiring out Chinese 2BG-6A planters in SPSTP mode, mounted on 12 HP two-wheel tractors was 2.6 implying that the planter operations at farm level were highly profitable (Miah Monayem et al., 2010). Similar profitability can be expected from the VMP, given its similar purchase price and field coverage capacity to the 2BG-6A planter (Haque et al., 2011)

Timeliness of crop operations can be critical to successful crop establishment, crop growth and ultimately to achieving the season's yield potential, especially in rainfed environments. Minimum tillage, which involves simultaneous seed and fertilizer placement in a small band of disturbed soil in a single operation can greatly accelerate the process of crop establishment. Minimum tillage and other one-pass planting operations are particularly effective in reducing turnaround time (Haque et al., 2004,Justice et al., 2004, Miah Monayem et al., 2009 and Islam et al., 2010), which is critically important in cropping systems producing 2–3 crops per year.

Timely operations under minimum tillage create opportunities for diversified crop rotations especially in double or triple cropping. Under such intensive cropping systems, there are often critical periods when labour is in short supply and the one-pass planting operations in CA enable that labour to be more productively and strategically employed. Even delays of a few days may be crucial for the success of sowing and for crop yield. For example, monsoon rice is commonly harvested from early November to late December in Bangladesh but failure to sow wheat on time reduces wheat yields by 1.3% per day of delay in planting after 1 December (Waddington et al., 2008). Lentil and chickpea also have relatively narrow sowing windows that overlap with the period of rice harvest. Late planting of these legumes results in decreased yield (Jeswani and Baldev, 1990).

Additional benefits may be achieved from increased soil carbon (C) sequestration and decreased greenhouse gas emissions, but more extensive research is needed to quantify this benefit across a broader range of soils and cropping systems. The amounts of C sequestered depend on crop residue retention. If, as discussed below, planters for two-wheel tractors can only operate effectively with light residue loads compared to planters for four-wheel tractors, there may be diminished C sequestration in soils. However, this remains to be tested. Conservation agriculture generally lowers greenhouse gas emissions by conserving soil carbon and decreasing fuel consumption. Decreases in CO_2 are equivalent to 2.6 kg of CO_2-equivalent L^{-1} of diesel fuel (Grace, 2003). Hence for a 27.2 L ha^{-1} saving in diesel, which is achievable with strip tillage (Haque et al., 2011b), there is an estimated decrease in CO_2-e emissions by 70.8 kg ha^{-1} $crop^{-1}$. The use of the planters mounted on 10% of the 350,000 power tillers in Bangladesh would be equivalent to a saving of 49.6 kt CO_2-e yr^{-1}.

Since development of the VMP in late 2009, 45 units of VMP has been commercially manufactured and marketed by the private companies in Bangladesh. Since November 2010, four VMPs were commercially used by small agricultural contractors for establishing a total of 87 ha of rice (mostly direct-seeded and un-puddled transplanted), wheat, mung bean, lentil, maize, black gram, chickpea in different tillage options; bed preparation for hand planting of potato (*Solanum tuberosum* L.); and single-pass shallow tillage for onion planting (Fig. 12). Four contractors provided services to 656 farmers at charges of US$ 26–38 per ha, depending on tillage mode and crop. The grain yield of wheat in the farmers VMP adaptation plots was 3.62 t ha^{-1} (n = 97); and the lentil grain yield 0.76 t ha^{-1} (n = 31). National average wheat yield is close to 2 t ha^{-1} (Waddington et al., 2008) and lentil yield 0.8–1.0 t ha^{-1}. The service providers have reported few technical or manufacturing defects of the VMP during operation. The VMP has created a demand for direct seeded rice (pre-monsoon season aus rice and monsoon season aman rice), however, due to severe weed infestation in the direct seeded rice plots farmers are reluctant to proceed until a suitable weed control option (either chemical or mechanical) has been demonstrated.

CA planters for four-wheel tractors

In developing countries where small four-wheeled tractors are used, simplified, low-cost versions of minimum tillage planters have been developed and adopted. An example is in the Indo-Gangetic Plain (IGP), comprising parts of India, Pakistan, Bangladesh and Nepal, where the area sown to no-till wheat increased from 12,800 ha in 1999–2000 to 2.4 million ha in 2005–2006 (Hobbs et al., 2008). This area comprises both small holder (<3 ha) and larger land holdings, although zero tillage with four-wheel tractors has mostly occurred on larger land holdings. Hobbs et al. (2008) attribute this rapid adoption to the use of farmer participatory approaches that encouraged farmers to experiment with the technology in their own fields and promotion of the local machinery manufacturers in the region to be partners in the programme. Local manufactures were able to develop affordable, effective drills based primarily on inverted-“T” coulter technology introduced from New Zealand. There was no direct reliance on imported equipment from areas already practicing CA but rather adaptation of the concepts used in those areas to prevailing tractor types, soil types, farming systems, and economic circumstances of the farming community. A major prerequisite to widespread adoption was low-cost and local manufacturing, repair, and servicing capability. This process is being trialled for wheat, barley, chickpea and lentil in northern Iraq and Syria where, based on low-cost Indian designs, minimum tillage planters are now being locally manufactured and increasingly used (Piggin, 2009).

Erenstein and Laxmi (2008) reported the net benefit of zero tillage over conventional tillage averaged US$ 97 ha^{-1} across studies of the rice–wheat cropping system of the IGP. The cost saving component of the net benefit (53%) was slightly higher than the yield increase component (47%). The average yield increase attributed to zero tillage of wheat across the IGP was estimated to be worth US$ 45 ha^{-1} (Erenstein and Laxmi, 2008). In India, minimum tillage by four-wheel tractors was estimated to increase profit to farmers by US$ 55–75 ha^{-1}.

A new agronomy

As has happened in large-scale commercial agriculture, a change to CA in small holder farms requires substantial adjustment of traditional agronomic practice (Baker and Saxton, 2007a), starting with fundamental changes in the ways in which farmers perceive the crop production process. This process is just beginning for small holder farmers reliant on hand, animal-drawn or two-wheel tractor mounted minimum tillage implements. Thus we can suggest some of the areas where major changes in agronomy are needed but it is only supported by limited data so far.

Mind set

One of the biggest impediments for widespread adoption of CA systems in southern Africa is the mind set (Wall, 2007). While farmers tend to accept more easily that crop production is possible without ploughing, it apparently is more difficult for people more removed from actual crop production (i.e. extensionists, researchers or university professors). To change the mind of a research director or even minister is even more difficult, however once change has been achieved they can be powerful movers and catalysts of CA. This could be observed in Zambia, when the Minister of Agriculture changed agriculture policies towards CA in 1999, and can be presently observed in Zimbabwe where CA is now very high on the political agenda. Once there is support from the Government there is scope for large scale adoption of CA technologies. Machinery manufacturers in southern Africa were initially very skeptical about moving away from the mouldboard ploughing system, a system they have used and managed since the early 1920s. However donor interest and a consistent push by various stakeholders towards ripper tine and animal traction systems has led to experimentation and design of new machinery and finally a change in mind set among the manufacturers towards equipment for sustainable agriculture.

The best way to change mind set towards minimum tillage is through technology demonstration and evaluation on-farm carried out in a multi-disciplinary mode, with farmers, extensionists, researchers, manufacturers, input and credit suppliers, etc. Traditional linear technology extension through knowledge pathways from on-station research to the farmer will not work with complex technologies such as CA and therefore new ways of extension are needed (Ekboir, 2002). In southern Africa best success has been achieved in extension of complex CA systems through multi-agent innovation networks (Rycroft and Kash, 1994 and Thierfelder and Wall, 2011). However this also involves changes in the behaviour of participants and *modus operandi* of technology transfer. Participatory research methods should be a central part of these multidisciplinary approaches, which need creation of a common language and open dissemination of information among diverse stakeholders. Continued interaction, testing and adaptation may eventually lead to new equipment and locally adapted CA cropping systems (Thierfelder and Wall, 2011).

Cropping pattern

Ability to sow a crop immediately following harvest of a preceding crop and without a pre-sowing tillage presents opportunities for changing cropping patterns and increasing cropping intensity. In rice–wheat cropping systems of the IGP, introduction of minimum tillage has shortened the turnaround time between rainy season rice and wheat—from 2 to 45 days with 2–12 passes to only one day with zero tillage (Hobbs et al., 2008). The immediate effect of this is higher wheat yields, as wheat can be planted closer to its optimum sowing time of early to mid-November. Also, earlier maturity of wheat increases opportunities for growing another crop, such as maize or mung bean, in the spring-summer period before the next rainy season rice crop. In Bangladesh, the rapid turnaround made possible with two-wheel tractor minimum tillage planters, along with use of shorter duration varieties, makes three-crop rotations more feasible. Examples of such rotations are rainy season rice–lentil/potato/rapeseed mustard–mung bean/maize (where "/"=or). With changes in cropping patterns and other changes to agronomy facilitated by CA, it will probably be found that different varietal characteristics than traditionally available will be required. That is, introduction of CA will increase demand for breeding of varieties better adapted to CA.

Another option for ensuring timely sowing of post-rice crops in the IGP is direct seeding, rather than transplanting, of the rainy season rice crop. In Haryana, India, direct seeding of rice in the rainy season with a zero till drill mounted on a four-wheel tractor can be more profitable than conventional transplanted rice (Saharawat et al., 2010). In Bangladesh, direct seeding of rainy season rice has also proven effective, giving yields of the same order or higher than conventional transplanted rice and 7–10 days earlier maturity (Mazid et al., 2008). Indian-type four-wheel tractor zero till drills are rare in Bangladesh, due to small field sizes, but Islam et al. (2011) have demonstrated direct seeding of rice by strip tillage with a VMP on a two-wheel tractor. This provides an option for moving to minimum tillage seeding of rice in Bangladesh, with its benefits of labour efficiency, saving water and ensuring early maturity of rice for optimum sowing of post-rice crops.

The appropriate planters for CA will vary with soil type, climate and cropping system (Baker and Saxton, 2007a). Where cropping is dominated by a single crop grown each year, a limited range of planter options may satisfy farmer needs. Where the cropping pattern involves 2–3 crops per year and a choice of a number of crops in each season, as in Bangladesh, the challenge to provide appropriate planters is greater. Clearly under such conditions flexibility and capacity to quickly change tillage mode and tillage settings (seed rate, row spacing) for the requirements of specific fields and farmers' preferences are critical (Haque et al., 2011). The VMP achieves a level of flexibility and versatility in planting operations far exceeding that of alternative planters. The ability of such devices as this to permit a rapid turnaround time between crops, and handle a wide variety of seed characteristics and planting configurations, increases options for another of the pillars of CA—diversity of crop rotations.

Residue management

Livestock play a crucial role in many small holder farming systems where animals contribute to food security, provide draft power and add to capital. They reduce the risk involved in such farming and are likely to remain integral to small holder farming into the future. Therefore, it is necessary to establish a compromise between crop residues used for retention on the field and for feed (Mueller et al., 2001 and Giller et al., 2011). Crop residues are also in demand as fuel and building material particularly in South Asia. Residue retention on CA fields in Asia and Africa is therefore insufficient in many cases. Various strategies have to be used to overcome this limitation: education and awareness creation, demonstration of benefits of residues, community agreements on grazing land and reinforcement of local by-laws on cattle roaming. Fencing with barbed wire or live fences could be another option although this can create tension within communities especially where communal grazing rights exist.

If residue retention is adequate, planters selected for implementation of CA need to be capable of handling the retained crop residue without compromising the accuracy of seed and fertilizer placement. Crop residue levels will vary widely among crop species, and between dryland and irrigated cropping systems. A key constraint to reliable sowing with two-wheel tractor planters will be residue length, particularly if the residue is unattached and not weakened by decomposition or weathering. Residue that is too tall can lead to blockages in seed and fertilizer dropping and loss of control in seed and fertilizer placement depth, particularly with zero tillage. The rotary blades ahead of the tines in strip tillage clear the standing stubble, reducing the risk of blockage by standing residue but loose heavy residue may still cause a problem. For four-wheel tractor minimum tillage planters, residue height should be adjusted relative to the minimum clearance height of tool bars and spacing between tines (Baker et al., 2007). With the VMP in strip tillage mode, stubble heights of wheat and rice of up to 50 cm have been managed. The optimal height of residue may also vary among crop species and between strip tillage, zero tillage and bed planting operations. Hence it is probable, but still untested, that zero tillage planters for two-wheel tractors will be less capable of handling heavy crop residue levels.

The level of crop residue is likely to affect field capacity of minimum tillage planters for two-wheel tractors. Complete residue retention would leave 5–7 t ha^{-1} of stubble after rice. In tests to date the VMP has been capable of satisfactory seed and fertilizer placement in fields with rice residue levels up to 3.3 t ha^{-1} (Haque et al., 2011). The field capacity of planters for two-wheel tractors such as VMP with heavy crop residue has not been tested. Further study is needed to determine the amounts of residues that can be handled in the case of a range of crop types such as wheat, maize, mung bean, and chickpea, and under different single-pass tillage modes. The ability of the planter to handle crop residue will depend in part on the row width and whether following crops in the rotation are planted in the inter-row space or along the row.

Levels of residue influence the effectiveness of herbicides by affecting the distribution of the herbicide and its contact with either the weeds or the soil surface. Hence the optimal level of residue for soil organic matter accumulation may differ from the optimum level for control of weeds using herbicides.

Planting pattern

A higher seed rate would be expected to be needed for broadcast sowing than line sowing because of uneven distribution and depth of placement when seed is broadcast. Thus it would be necessary to re-determine optimum seed rates for mechanized row sowing of crops traditionally sown by broadcasting and with full tillage. Attempts have been made to calibrate seed rates for lentil and chickpea sown at 40 cm row spacing by VMP with strip tillage in the 2009–2010 season in Bangladesh (Table 2). Aerial biomass and grain yield do decline with decreasing seed rate, but not significantly due to the variability inherent in this experimentation. Low yields and high plot-to-plot variability were obtained due to excess soil moisture at sowing in both crops and seedling damage by collar rot (*Sclerotium rolfsii*) and infestation by Botrytis grey mould (*Botrytis cinerea*) and pod borer (*Helicoverpa armigera*) in chickpea. However, there is an indication that moderate reductions in seed rate can be achieved without significantly reducing yield of lentil and chickpea but many further such studies are needed to be able to decide on optimum seed rates for particular situations. A range of both within-row seed rates and row spacings need to be examined. For grain legumes at least, optimum seed rate depends on a delicate balance between seedling death by fungal pathogens, extent of infestation by foliar disease (Allen and Lenné, 1998) and insect pests, soil moisture status through the crop cycle (Beech and Leach, 1989) and producing sufficient vegetative growth to support yield formation.

Fertilizer

Full tillage results in rapid mineralization of organic matter and it homogenizes the distribution of nutrients to the depth of tillage. Tillage depth may vary from 7 to 20 cm depending on the form of tillage and whether it is mechanized or animal drawn. Rotary tillage with 12 HP two-wheel tractors in Bangladesh is relatively shallow (6 cm). However, within this tilled zone roots have relatively unrestricted access to nutrients whether from mineralized SOM, from other soil reserves, or from fertilizer residues, so long as the soil remains moist enough for active root exploration. When topsoil dries, root access to the nutrients in the tilled zone diminishes. Minimum soil disturbance under CA generally results in stratification of nutrients with highest concentrations, particularly phosphorus (P) and potassium (K), either close to the surface or in planting rows (Howard et al., 1999). Minimum tillage increases fertilizer nitrogen (N) requirements at least in the initial years after transition to CA due to N immobilization by crop residues. Hence in those areas where farmers are unable to afford increased N fertilizer, the conversion to CA may decrease crop yields during the transitional period (Giller et al., 2009).

Minimum soil disturbance with CA generally involves fertilizer placement with seed, under seed or beside the seed. Hence there is a risk of fertilizer toxicity, especially with soluble fertilizers on sandy or silty soils (Kabir et al., 2010), but this depends on the rate of application, plant species and the soil moisture levels at sowing. Nitrogen, P or K fertilizers are most likely to lead to toxicity. Consequently it is common to topdress N and K fertilizer after crop establishment provided there is sufficient post-sowing soil moisture to allow root uptake of the supplied nutrients.

Provided placement of fertilizer in furrows adjacent to the seed does not cause toxicity, fertilizer use efficiency should be increased as compared with broadcasting (Bullen et al., 1983). In soils in Bangladesh where the recommended rate of P application for lentil and chickpea for broadcast application is 20 kg P ha^{-1}, preliminary studies by the authors at the locations of seed rate trials (Table 2) indicated a marginal yield reduction of these crops sown by VMP with strip tillage when the P rate was halved. Seed and P fertilizer were delivered together in the slot and no toxicity was observed. However, other constraints as mentioned for seed rate trials contributed to low and variable yields in the P rate studies and much more experimentation is needed to adequately quantify these effects. A decrease in fertilizer rate with minimum tillage would be expected due not only to fertilizer placement in the crop row but also, over a longer period of practicing CA, to improved nutrient supplying capacity of the soil due to SOM build-up and increased surface soil moisture retention extending the period of availability of near-surface nutrients. Requirements for N fertilizer are likely to be highly variable and site specific depending on the amount of crop residue retention and its extent of decomposition, which determines the balance between immobilization and mineralization of soil N (Giller et al., 2009).

Weed management

Changing from full tillage to minimum or zero tillage necessarily changes the nature of weed infestation in crops. While full tillage can kill most growing weeds to produce a clean seedbed for sowing of the crop it also stimulates germination of seeds of weeds that can compete with crop plants during the growing season. With minimum tillage this stimulation of weed seed germination is diminished but the crop still faces competition from weeds already growing at sowing time as well as those emerging after crop sowing. Such a change in tillage method would also change the suite of weed species emerging and weed ecology generally.

If small holder farmers adopted minimum tillage and residue retention then continued reliance on traditional manual weed control measures would be difficult (Wall, 2007 and Steiner and Twomlow, 2003). Although row sowing may permit inter-row cultivation with manual implements, crop residue would interfere with this process and in any case careful hand weeding would still be required near crop rows. Further, topsoil would be disturbed, thus negating CA advantages. In large-scale commercial agriculture there is heavy reliance on herbicides to control weeds that would otherwise be killed by thorough tillage. In small holder agriculture relevant herbicides are generally not available or affordable, and local knowledge on their most effective and safe use is usually inadequate.

If minimum tillage is to be adopted by small holder farmers then it is imperative that integrated weed management strategies be simultaneously adopted. This would likely require use of herbicides but if they are introduced it would be essential to educate suppliers and farmers as to their effective and safe use (Vogel, 1994). A particular concern is development of herbicide resistance among major weed species, if not used at appropriate rates or herbicide chemicals are not used in rotation (Powles and Yu, 2010). Other non-chemical options for integrated weed management in small holder cropping systems rely on a holistic understanding of crop and weed ecology. They include using crop rotations unfavourable to major weed species, use of cover crops, adjusting sowing time and procedure, use of competitive crop genotypes, arranging planting pattern, minimizing contamination of crop seed with weed seeds, and adjusting fertilizer strategy to minimize weed competition (Vogel, 1995 and Bàrberi, 2002).

Pests and diseases

Changing from broadcast sowing to line sowing is particularly advantageous for legume crops as a result of their susceptibility to various diseases (Allen and Lenné, 1998) and insect pests (Edwards and Singh, 2006). In the case of foliar diseases, such as ascochyta blight (*Ascochyta rabiei*) and botrytis grey mould in chickpea, disease development is impeded by open and well-aerated canopies (Reddy et al., 1993 and Gan et al., 2006). This situation can be obtained with row planting, as compared with random distribution of plants in broadcast planting, while maintaining a plant population adequate for maximum yield. Use of an easily adjustable planter such as the VMP permits ready adjustment of row width according to expected disease severity. It has been similarly shown that insect damage is less severe with row rather than broadcast planting, such as for the case of *Helicoverpa armigera* pod borer on chickpea (Sithanantham and Reed, 1979).

However, a shift to CA involving an increase in crop residue left on the soil surface can increase severity of particular diseases (Bockus and Shroyer, 1998). Both foliar infecting and root infecting fungi can benefit from the carryover of crop residue through mechanisms such as survival of spores on host plant residue, the residue providing substrate for a saprophytic phase, and the mulching providing favourable soil moisture, temperature and nutritional conditions for fungal survival, growth and reproduction. An example is the carryover of *Sclerotium rolfsii*, an important pathogen of seedlings of many legume crops, on crop debris as a saprophyte, and thus increasing the pathogen load on subsequent crops (Allen and Lenné, 1998). An increase in a particular plant pathogen as a result of introduction of CA is best countered by ensuring that diverse crop rotation is included in the CA strategy, to break disease cycles. Nevertheless, CA practices such as minimum tillage and mulching may reduce severity of some soil pathogens, by creating soil conditions unfavourable to them (e.g. increased soil moisture under CA discouraging dry root rots which are favoured by drier soils) or more favourable to their microbial antagonists (Bockus and Shroyer, 1998).

It is likely that, in a particular environment, a change to CA practices will substantially change the microbial ecological balance, thereby causing previously minor or new pests and diseases to assume importance and once major diseases to subside in prevalence or severity. Thus such changes after implementation of CA will require judicious monitoring of pest and disease status so as to be able to take timely remedial action.

Future Directions

Quantification of effects of CA on crops and soils

The effects of CA on crops and soils evolve over time. There are short term effects on nutrient availability that require alterations in fertilizer recommendations for the transitional phase. There are longer term changes in mineralization of organic matter, the spectrum of weeds, and prevalent diseases and insects. Hence there is a strong case for long term trials strategically placed in regions that are implementing CA. It is preferable that they be placed on-farm, despite the lesser control possible than in fenced-off research stations, to ensure that the results obtained are indeed relevant to the extrapolation area. Such trials need to take temporal and spatial measurements of parameters determining soil quality, the relevant beneficial and pathogenic soil organisms, aerial pests and diseases, as well as crop characteristics of growth, phenology, yield and quality. In view of often sub-optimal soil moisture levels in rainfed environments, it would be particularly instructive to quantify the effect of CA components on soil moisture availability to crops.

Giller et al., 2009 and Giller et al., 2011 have questioned the universal suitability of CA practices. Reviewing results from Sub-Saharan Africa, they point out that CA has not produced the generalized benefits reported above, indeed decreases in yield are common. They argue that lack of herbicides may increase the labour requirements for weeding in CA, and shift the burden of weed control to women in the household. If herbicides are unavailable or too costly for small holder farmers to use, the extra labour required for weed control may result in greater labour requirements in CA than conventional cropping. The lack of key inputs in local markets, as is common in SSA, may limit the yield benefits from CA. In addition, under low crop productivity, crop residue levels may be too low to achieve the benefits of soil cover. Alternatively, the competing requirements for crop residues, as animal feed, or as domestic fuel for cooking, may leave so little organic matter input to soils that limited change in SOM can be expected. Hence it is important to define the domains where CA will produce benefits on smallholder farms and importantly to identify situations where it will not. Moreover, it is necessary to better understand the benefits from each of the core components of CA: minimum soil disturbance; maintaining soil cover and; diverse rotation (Giller et al., 2009). A better understanding of the role of each component may help to explain why CA produces benefits in most situations but not in others.

Facilitating continued innovation

The development of CA for small holder farmers, whether with animal draft power or tractors needs to be pursued as a partnership between farmers, service providers and machinery manufacturers, researchers and extensionists. Experience elsewhere in the world suggests that such partnerships are conducive to innovation, adaptation of technology to farmer needs and adoption on farms (e.g. Brazil—Pieri et al., 2002). Adoption of CA is facilitated by: on-going machinery modifications to allow more flexibility in seeding; development of cost-effective spray technology for weed control using herbicides; improved crop resistance to stubble-borne diseases; more diverse crop and rotation options; breeding herbicide resistant crops and; the use of broad spectrum herbicides (Thomas et al., 2007). Value chain analysis of the farm machinery and planter market systems will need to be mapped to identify key bottlenecks to adoption. Such studies should probably include the crop residue value chain as a possible impediment to the retention of residues in CA systems on small holder farms.

The average land holding in Bangladesh is less than 1 ha, which does not justify purchase of planters for two-wheel tractors by individual farmers. Similar constraints will exist in the eastern IGP and many other areas where small holder farming is prevalent. Currently, more than 400,000 two-wheel tractors are being used in Bangladesh mostly on a contract hire basis. There are more than 1000 CA machinery custom hire contractors providing planting and other services to 60–90 neighbouring farmers each. Networks have been built among the farmers and service providers, several small farm machinery marketing companies, some very small local machinery manufacturers, and research and extension organizations in 25 districts of Bangladesh. Access to interest-free loans has been facilitated, along with training and advice to farmers on how to access machinery and CA. In the last 2–3 years, at least two importers, five farm machinery manufacturers and distributors of the new CA machinery including the VMP have started business. Thus the components for the sustainable implementation of CA including farm machinery on a commercial basis have been put in place in Bangladesh. Stakeholder partnerships and networks need further strengthening to further advance concepts of CA service provision.

Monitoring adoption and impact

In introducing minimum tillage and the other components of CA, residue retention and diverse rotations, it is recommended that a formal procedure for measuring adoption and impact on livelihoods of small holder farming families be implemented. Annual tracking of adoption permits early identification of adoption constraints, and thus prompts early action to address them. At the beginning of the adoption process, as is the present situation for minimum tillage planters for two-wheel tractors, it is particularly recommended to conduct an *ex ante* analysis of economic return. For a given region this involves estimation of the time lag of adaptive research before significant adoption begins, the expected ceiling level of adoption, the shape of the adoption curve and the time to reach that ceiling, and the net present value (NPV, expected financial return less investment cost). Such an analysis done for introduction of zero tillage of wheat with four-wheel tractors in the IGP of India calculated conservative scenario NPV of US$ 96 million, benefit cost ratio of 39 and internal rate of return of 57% (Laxmi et al., 2007). Based on actual data from where zero tillage had been adopted they assumed that zero tillage produced yield gains of 6% and reduced input costs by 5%, and that ceiling level of adoption would be 33% to be reached about 10 years after the beginning of adoption.

Actual adoption figures for zero tillage wheat in the Indo-Gangetic Plain of India appear to be following this scenario (Hobbs et al., 2008). Although many assumptions are involved it is suggested that an *ex ante* analysis be conducted for the adoption of minimum tillage with two-wheel tractors in Bangladesh; adoption parameters found for zero tillage wheat in the IGP of India could at least guide parameters to use in Bangladesh. Such an analysis will help establish the potential for minimum tillage planters on two-wheel tractors in Bangladesh and the likely returns for pursuing this innovation. Once such an analysis is available, and if it is similarly favourable to the zero tillage wheat in India example, it would be easier to attract the necessary investments to fund the required research, adaptation, coordination and extension.

To obtain the data necessary for both *ex ante* and *ex post* impact analyses procedures need to be embedded to permit annual measurement of sales of planter units, their mean area coverage, and net benefits in terms of yield increases and cost savings on inputs. If and when introduction of minimum tillage planters also encourages increased residue retention and diverse crop rotation then benefits of these factors will also need to be captured and incorporated.

Calculation of benefits associated with environmental improvements, such as improvements in soil quality and increased water and nutrient use efficiency, will depend on outcomes of long term trials and observations referred to in Section 5.1. An important component of the adoption and impact data set would be that collected directly from farm families, in surveys, interviews, focus discussion groups and case studies, to be able to understand how introduction of CA or its components is actually affecting livelihoods of small holder families.

Conclusion

The key to furthering CA among small holders is development and deployment of affordable and effective minimum tillage implements. In Sub-Saharan Africa several manual CA seeding systems such as dibble sticks, planting basins and jab-planters are promoted along with mechanized animal traction systems such as different types of tine rippers and direct planters. Minimum tillage implements compatible with two-wheel tractors are now reaching early stages of adoption, mainly in South Asia. These developments provide an opening for the other two main pillars of CA—more ground cover and more diverse crop rotations. Where two-wheel tractors have become ubiquitous, there has been a consequent decline in draft animals thereby rendering more crop residue available for ground cover.

However, for small holder, resource-constrained farmers various bottlenecks to adoption of CA remain, as elaborated by Giller et al., 2009 and Giller et al., 2011, despite the recent emergence of suitable minimum tillage implements. A particular challenge is development of integrated weed management strategies that will at least compensate the weed control afforded by conventional tillage. Although herbicide chemicals exist for most weed situations, access of small holders to them and the knowledge required for their effective and safe use is limited. Priority is thus required in establishing integrated weed management strategies for particular cropping situations, drawing upon the entire toolkit of options available—herbicides, mechanical, rotations, weed seed bank management, etc.

Introduction of minimum tillage also demands radical changes to other aspects of conventional agronomy, such as planting pattern, fertilizer use and pest and disease management. There is obviously a need for re-writing of the research originally targeted at conventional agriculture (e.g. full tillage and broadcast systems), but it is urged that in this case the research be done in full participatory mode with farmers on their fields. Indeed, introduction of CA in the Americas, Australia and the IGP of India has pioneered methods of participatory on-farm research, development and extension, and this mode needs to be further pursued for CA for small holders. A major compulsion for this is that, although the principles of CA have wide applicability across many agro-ecological and physiographical environments, they need to be adjusted to a farmer's particular conditions to make them valid and applicable.

Acknowledgements

Studies reported here relating to development of seeding devices for two-wheel tractors since 2006 have been supported by the Australian Centre for International Agricultural Research (ACIAR) projects LWR/2005/001 and CIM/2007/027 and by CIMMYT.

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Table 1.

Summary of advantages of minimum tillage over conventional, full tillage in large-scale commercial agriculture.

Input economics	**Soil quality**	**Environment**
Fuel conservation	Increased soil organic matter	Reduced soil erosion
Less labour cost	Increased stored soil nitrogen	Less irrigation requirement
Time saving and flexibility	Improved nutrient dynamics	Less pollution of waterways
Longer machinery life	Improved soil structure	Lower net CO_2 emissions
Less fertilizer required	More earthworms, soil fauna	
	Improved aeration	
	Improved infiltration	
	Soil water conservation	
	Moderated soil temperatures	
	Reduced weed germination	
	Improved trafficability	

Source: Adapted from Baker and Saxton (2007b) and Reicosky and Saxton (2007).

Table 2. Effect of seed rate on grain and straw yield of lentil and chickpea sown by VMP in farmers' fields, Thakurgaon Sadar, Bangladesh, 2009–2010 ($n = 4$).

Lentil			Chickpea		
Seed rate (kg ha^{-1})	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Seed rate (kg ha^{-1})	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})
34	402	566	37.5	328	1239
25.5 (75%)[a]	358	514	31 (87%)	292	1189
17 (50%)	278	372	25 (63%)	215	941
SE[b]	95	110	SE	33	130

[a]Percentage of recommended broadcast seed rate, in first row.

[b]Standard error of difference between any two means; there were no significant differences between any treatments at $P < 0.05$.

Source: Data from ACIAR project LWR/2005/001.

Fig. 1. Dibble stick (Photograph: P. Wall).

Fig. 2. Manual dug planting basins (Photograph: C. Thierfelder).

Fig. 3. Jab-planter (Photograph: C. Thierfelder).

Fig. 4. Ripper tine (Photograph: C. Thierfelder).

Fig. 5. Animal traction direct planter (Photograph: C. Thierfelder).

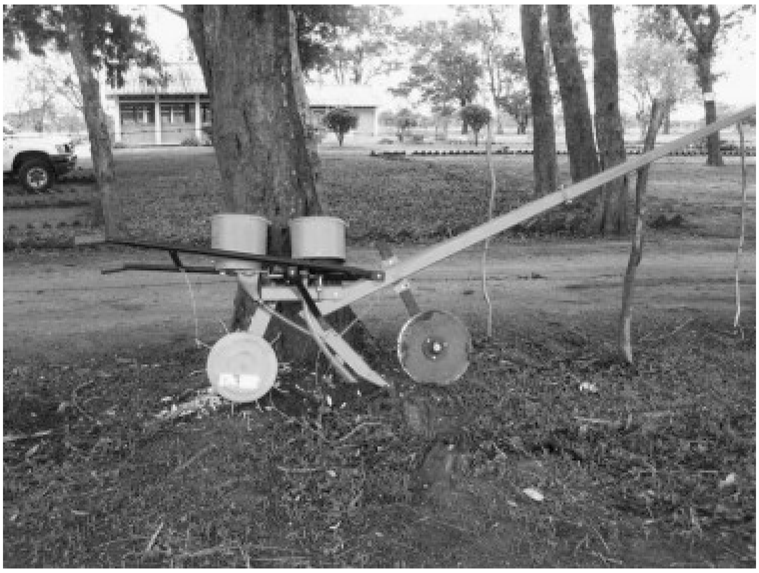
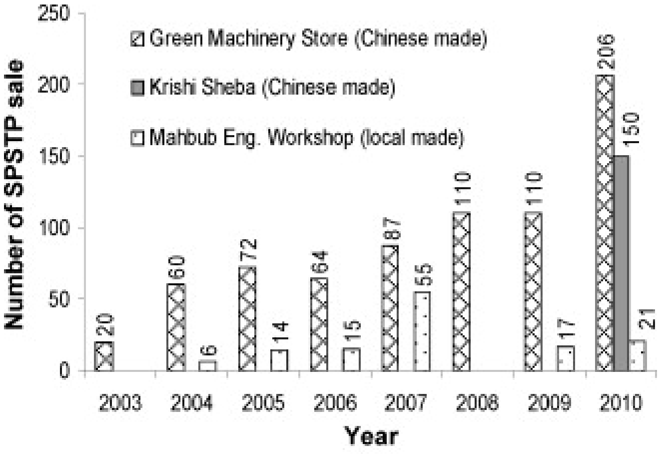


Fig. 6. Status of SPSTP use in Bangladesh.



Source: Information collected from import and sale record.

Fig. 7. The original BARI/CIMMYT tined zero till seed drill (Photograph: M.E. Haque).

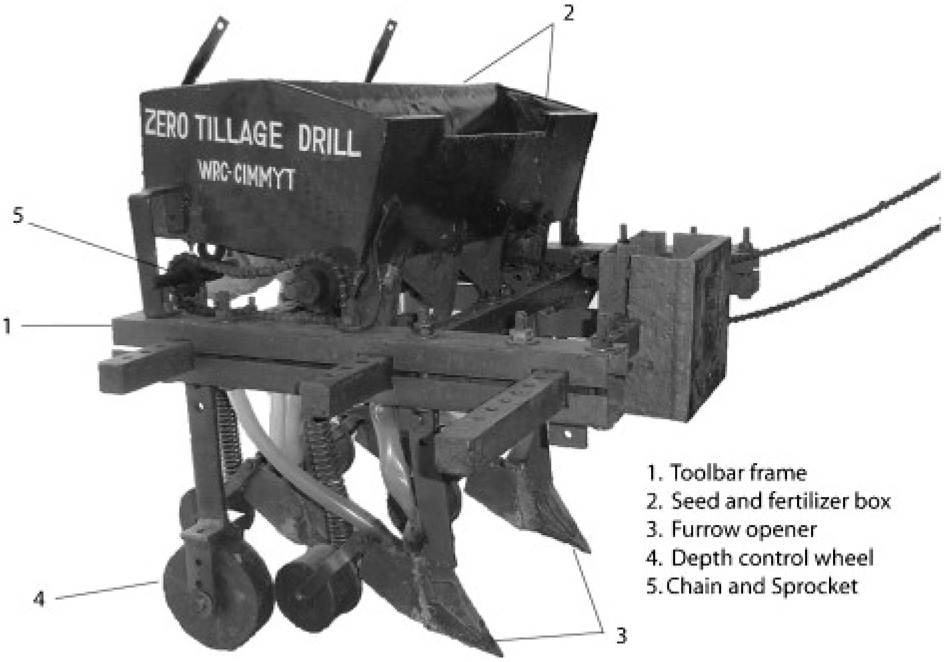


Fig. 8. The improved ACIAR-Rogro tined zero till seed drill (Photograph: R.J. Esdaile).

Fig. 9. Some optional soil engaging tools to fit the two-wheel tractor seed drills (Photograph: R.J. Esdaile).

Fig. 10. A Bangladesh-made two-wheel tractor seed drill in strip tillage mode (Photograph: R.J. Esdaile).

Fig. 11. The versatile multi-crop planter (VMP) (Photograph: M.E. Haque).

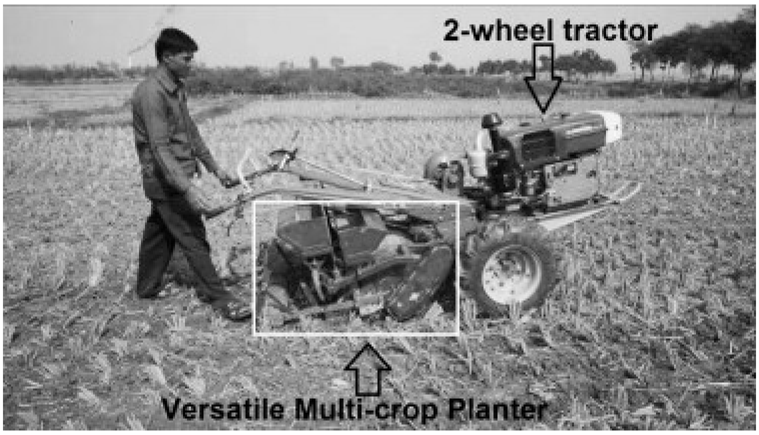


Fig. 12. Area sown to different crops and numbers of farmers serviced by four VMPs in northern Bangladesh during November 2010–April 2011.