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The role of conservation agriculture in sustainable agriculture

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The paper focuses on conservation agriculture (CA), defined as minimal soil disturbance (no-till, NT) and permanent soil cover (mulch) combined with rotations, as a more sustainable cultivation system for the future. Cultivation and tillage play an important role in agriculture. The benefits of tillage in agriculture are explored before introducing conservation tillage (CT), a practice that was borne out of the American dust bowl of the 1930s. The paper then describes the benefits of CA, a suggested improvement on CT, where NT, mulch and rotations significantly improve soil properties and other biotic factors. The paper concludes that CA is a more sustainable and environmentally friendly management system for cultivating crops. Case studies from the rice–wheat areas of the Indo-Gangetic Plains of South Asia and the irrigated maize–wheat systems of Northwest Mexico are used to describe how CA practices have been used in these two environments to raise production sustainably and profitably. Benefits in terms of greenhouse gas emissions and their effect on global warming are also discussed. The paper concludes that agriculture in the next decade will have to sustainably produce more food from less land through more efficient use of natural resources and with minimal impact on the environment in order to meet growing population demands. Promoting and adopting CA management systems can help meet this goal.

Keywords: conservation agriculture; direct seeding; zero-tillage; rice–wheat systems; bed planting; mulching

1. INTRODUCTION

Conservation agriculture (CA) defined (see FAO CA web site: <http://www.fao.org/ag/ca/1a.html>) as minimal soil disturbance (no-till, NT) and permanent soil cover (mulch) combined with rotations, is a recent agricultural management system that is gaining popularity in many parts of the world. Cultivation is defined by the Oxford English dictionary as ‘the tilling of land’, ‘the raising of a crop by tillage’ or ‘to loosen or break up soil’. Other terms used in this dictionary include ‘improvement or increase in (soil) fertility’. All these definitions indicate that cultivation is synonymous with tillage or ploughing.

The other important definition that has been debated and defined in many papers is the word ‘sustainable’. The Oxford English dictionary defines this term as ‘capable of being borne or endured, upheld, defended, maintainable’. Something that is sustained is ‘kept up without intermission or flagging, maintained over a long period’. This is an important concept in today’s agriculture, since the human race will not want to compromise the ability of its future offspring to produce their food needs by damaging the natural resources used to feed the population today.

This paper will introduce and promote CA as a modern agricultural practice that can enable farmers in many parts of the world to achieve the goal of

sustainable agricultural production. But first, the paper discusses some issues related to tillage.

2. CULTIVATION TECHNIQUES OR TILLAGE

The history of tillage dates back many millennia when humans changed from hunting and gathering to more sedentary and settled agriculture mostly in the Tigris, Euphrates, Nile, Yangste and Indus river valleys (Hillel 1991). Reference to ploughing or tillage is found from 3000 BC in Mesopotamia (Hillel 1998). Lal (2001) explained the historical development of agriculture with tillage being a major component of management practices. With the advent of the industrial revolution in the nineteenth century, mechanical power and tractors became available to undertake tillage operations; today, an array of equipment is available for tillage and agricultural production. The following summarizes the reasons for using tillage.

- (i) Tillage was used to soften the soil and prepare a seedbed that allowed seed to be placed easily at a suitable depth into moist soil using seed drills or manual equipment. This results in good uniform seed germination.
- (ii) Wherever crops grow, weeds also grow and compete for light, water and nutrients. Every gram of resource used by the weed is one less gram for the crop. By tilling their fields, farmers were able to shift the advantage from the weed to the crop and allow the crop to grow without

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One contribution of 16 to a Theme Issue ‘Sustainable agriculture I’.

competition early in its growth cycle with resulting higher yield.

- (iii) Tillage helped release soil nutrients needed for crop growth through mineralization and oxidation after exposure of soil organic matter to air.
- (iv) Previous crop residues were incorporated along with any soil amendments (fertilizers, organic or inorganic) into the soil. Crop residues, especially loose residues, create problems for seeding equipment by raking and clogging.
- (v) Many soil amendments and their nutrients are more available to roots if they are incorporated into the soil; some nitrogenous fertilizers are also lost to the atmosphere if not incorporated.
- (vi) Tillage gave temporary relief from compaction using implements that could shatter below-ground compaction layers formed in the soil.
- (vii) Tillage was determined to be a critical management practice for controlling soil-borne diseases and some insects.

There is no doubt that this list of tillage benefits was beneficial to the farmer, but at a cost to him and the environment, and the natural resource base on which farming depended. The utility of ploughing was first questioned by a forward-looking agronomist in the 1930s, Edward H. Faulkner, in a manuscript called 'Ploughman's Folly' (Faulkner 1943). In a foreword to a book entitled 'Ploughman's folly and a second look' by EH Faulkner, Paul Sears notes that:

Faulkner's genius was to question the very basis of agriculture itself—the plough. He began to see that the curved moldboard of the modern plough, rather than allowing organic matter to be worked into the soil by worms and other burrowing animals, instead buries this valuable material under the subsoil where it remains like a wad of undigested food from a heavy meal in the human stomach.

(Faulkner 1987, p. x)

The tragic dust storm in the mid-western United States in the 1930s was a wake-up call to how human interventions in soil management and ploughing led to unsustainable agricultural systems. In the 1930s, it was estimated that 91 Mha of land was degraded by severe soil erosion (Utz *et al.* 1938); this area has been dramatically reduced today.

3. CONSERVATION TILLAGE AND CONSERVATION AGRICULTURE

Since the 1930s, during the following 75 years, members of the farming community have been advocating a move to reduced tillage systems that use less fossil fuel, reduce run-off and erosion of soils and reverse the loss of soil organic matter. The first 50 years was the start of the conservation tillage (CT) movement and, today, a large percentage of agricultural land is cropped using these principles. However, in the book 'No-tillage seeding', Baker *et al.* (2002; a second edition of this excellent book was published in 2006) explained 'As soon as the modern concept of reduced tillage was recognized, everyone, it seems,

invented a new name to describe the process'. The book goes on to list 14 different names for reduced tillage along with rationales for using these names. The book is also an excellent review of the mechanization and equipment needs of no-tillage technologies. Baker *et al.* (2002) defined CT as:

the collective umbrella term commonly given to no-tillage, direct-drilling, minimum-tillage and/or ridge-tillage, to denote that the specific practice has a conservation goal of some nature. Usually, the retention of 30% surface cover by residues characterizes the lower limit of classification for conservation-tillage, but other conservation objectives for the practice include conservation of time, fuel, earthworms, soil water, soil structure and nutrients. Thus residue levels alone do not adequately describe all conservation tillage practices.

(Baker *et al.* 2002, p. 3)

This has led to confusion among the agricultural scientists and, more importantly, the farming community. To add to the confusion, the term 'conservation agriculture' has recently been introduced by the Food and Agriculture Organization (see FAO web site), and others, and its goals defined by FAO as follows:

Conservation agriculture (CA) aims to conserve, improve and make more efficient use of natural resources through integrated management of available soil, water and biological resources combined with external inputs. It contributes to environmental conservation as well as to enhanced and sustained agricultural production. It can also be referred to as resource efficient or resource effective agriculture.

(FAO)

This obviously encompasses the 'sustainable agricultural production' need that all mankind obviously wishes to achieve. But this term is often not distinguished from CT. The FAO mentions in its CA website that:

Conservation tillage is a set of practices that leave crop residues on the surface which increases water infiltration and reduces erosion. It is a practice used in conventional agriculture to reduce the effects of tillage on soil erosion. However, it still depends on tillage as the structure forming element in the soil. Never the less, conservation tillage practices such as zero tillage practices can be transition steps towards Conservation Agriculture.

In other words, CT uses some of the principles of CA but has more soil disturbance.

4. CONSERVATION AGRICULTURE DEFINED

The FAO has characterized CA as follows:

Conservation Agriculture maintains a permanent or semi-permanent organic soil cover. This can be a growing crop or dead mulch. Its function is to protect the soil physically from sun, rain and wind and to feed soil biota. The soil micro-organisms and soil fauna take over the tillage function and soil nutrient balancing. Mechanical tillage disturbs this process. Therefore, zero or minimum tillage and direct seeding are

Table 1. Extent of no-tillage adoption worldwide. (adapted from Derpsch 2005; ** includes area in India, Pakistan, Bangladesh and Nepal in South Asia.)

country	area under no-tillage (Mha) 2004/2005
USA	25.30
Brazil	23.60
Argentina	18.27
Canada	12.52
Australia	9.00
Paraguay	1.70
Indo-Gangetic Plains (**)	1.90
Bolivia	0.55
South Africa	0.30
Spain	0.30
Venezuela	0.30
Uruguay	0.26
France	0.15
Chile	0.12
Colombia	0.10
China	0.10
others (estimate)	1.00
total	95.48

important elements of CA. A varied crop rotation is also important to avoid disease and pest problems.

(see FAO web site)

Data reported by Derpsch (2005) indicate that the extent of no-tillage adoption worldwide is just over 95 Mha. This figure is used as a proxy for CA although not all of this land is permanently no-tilled or has permanent ground cover. Table 1 details the extent of no-tillage by country worldwide. Six countries have more than 1 Mha. South America has the highest adoption rates and has more permanent NT and permanent soil cover. Both Argentina and Brazil had significant lag periods to reach 1 Mha in the early 1990s and then expanded rapidly to the present-day figures of 18.3 and 23.6 Mha, respectively, for these countries. By adopting the no-tillage system, Derpsch (2005) estimated that Brazil increased its grain production by 67.2 million tons in 15 years with additional revenue of 10 billion dollars. Derpsch also estimated that at an average rate of $0.51 \text{ t ha}^{-1} \text{ yr}^{-1}$ Brazil sequestered 12 million tons of carbon on 23.6 Mha of no-tillage land. Tractor use is also significantly reduced saving millions of litres of diesel.

The three key principles of CA are permanent residue soil cover, minimal soil disturbance and crop rotations. The FAO recently added controlled traffic to this list. Each of these will be briefly dealt with before providing some case studies. Table 2 shows a comparison of CA with CT and traditional tillage (TT).

(a) *Permanent or semi-permanent organic soil cover*

Unger *et al.* (1988) reviewed the role of surface residues on water conservation and indicates that this association between surface residues, enhanced water infiltration and evaporation led to the adoption of CT after the 1930s dust bowl problem. Research since that time has documented beyond doubt the importance of surface residues on soil water conservation and

reduction in wind and water erosion (Van Doran & Allmaras 1978; Unger *et al.* 1988). Bissett & O'Leary (1996) showed that infiltration of water under long-term (8–10 years) conservation tillage (zero and sub-surface tillage with residue retention) was higher compared to conventional tillage (frequent plowing plus no residue retention) on a grey cracking clay and a sandy loam soil in south-eastern Australia. Allmaras *et al.* (1991) reviewed much of the literature on CT up to that time and goes on to describe a whole array of CT-planting systems operating in the US, their adoption and benefits.

This paper will not go into detail about other soil-conserving practices that are used throughout the world and over time, like terracing or contour bunds that are essentially designed to prevent soil erosion on sloping lands. Lal (2001) described some of these systems and notes that the effectiveness of these systems depends on proper construction and regular maintenance; if not done properly degradation can be catastrophic.

Kumar & Goh (2000) reviewed the effect of crop residues and management practices on soil quality, soil nitrogen dynamics and recovery and crop yield. The review concluded that crop residues of cultivated crops are a significant factor for crop production through their effects on soil physical, chemical and biological functions as well as water and soil quality. They can have both positive and negative effects, and the role of agricultural scientists is to enhance the positive effects.

This paper will restrict the discussion of crop residues to their benefits when used as mulch. Crop residues result when a previous crop is left anchored or loose after harvest or when a cover crop (legume or non-legume) is grown and killed or cut to provide mulch. Externally applied mulch in the form of composts and manures can also be applied, although the economics of transport of this bulky material to the field may restrict its use to higher-value crops like vegetables.

The energy of raindrops falling on a bare soil result in destruction of soil aggregates, clogging of soil pores and rapid reduction in water infiltration with resulting run-off and soil erosion. Mulch intercepts this energy and protects the surface soil from soil aggregate destruction, enhances the infiltration of water and reduces the loss of soil by erosion (Freebairn & Boughton 1985; McGregor *et al.* 1990; Dormaar & Carefoot 1996). Topsoil losses of 46.5 t ha^{-1} have been recorded with TT on sloping land after heavy rain in Paraguay compared with 0.1 t ha^{-1} under NT cultivation (Derpsch & Moriya 1999). NT plus mulch reduces surface soil crusting, increases water infiltration, reduces run-off and gives higher yield than tilled soils (Cassel *et al.* 1995; Thierfelder *et al.* 2005). Similarly, the surface residue, anchored or loose, protects the soil from wind erosion (Michels *et al.* 1995). The dust bowl is a useful reminder of the impacts of wind and water erosion when soils are left bare.

Surface mulch helps reduce water losses from the soil by evaporation and also helps moderate soil temperature. This promotes biological activity and enhances nitrogen mineralization, especially in the surface layers (Dao 1993; Hatfield & Pruegar 1996). This is a very important factor in tropical and sub-tropical environments but has been shown to be a

Table 2. A comparison of tillage, conservation tillage (CT) and conservation agriculture (CA) for various issues.

issues	traditional tillage (TT)	conservation tillage (CT)	conservation agriculture (CA)
practice	disturbs the soil and leaves a bare surface	reduces the soil disturbance in TT and keeps the soil covered	minimal soil disturbance and soil surface permanently covered
erosion	wind and soil erosion: maximum	wind and soil erosion: reduced significantly	wind and soil erosion: the least of the three
soil physical health	the lowest of the three	significantly improved	the best practice of the three
compaction	used to reduce compaction and can also induce it by destroying biological pores	reduced tillage is used to reduce compaction	compaction can be a problem but use of mulch and promotion of biological tillage helps reduce this problem
soil biological health	the lowest of the three owing to frequent disturbance	moderately better soil biological health	more diverse and healthy biological properties and populations
water infiltration	lowest after soil pores clogged	good water infiltration	best water infiltration
soil organic matter	oxidizes soil organic matter and causes its loss	soil organic build-up possible in the surface layers	soil organic build-up in the surface layers even better than CT
weeds	controls weeds and also causes more weed seeds to germinate	reduced tillage controls weeds and also exposes other weed seeds for germination	weeds are a problem especially in the early stages of adoption, but problems are reduced with time and residues can help suppress weed growth
soil temperature	surface soil temperature: more variable	surface soil temperature: intermediate in variability	surface soil temperature: moderated the most
diesel use and costs	diesel use: high	diesel use: intermediate	diesel use: much reduced
production costs	highest costs	intermediate costs	lowest costs
timeliness	operations can be delayed	intermediate timeliness of operations	timeliness of operations more optimal
yield	can be lower where planting delayed	yields same as TT	yields same as TT but can be higher if planting done more timely

hindrance in temperate climates due to delays in soil warming in the spring and delayed germination (Schneider & Gupta 1985; Kaspar *et al.* 1990; Burgess *et al.* 1996; Swanson & Wilhelm 1996). Fabrizzi *et al.* (2005) showed that NT had lower soil temperatures in the spring in Argentina, but TT had higher maximum temperatures in the summer, and that average temperatures during the season were similar.

Karlen *et al.* (1994) showed that normal rates of residue combined with zero-tillage resulted in better soil surface aggregation, and that this could be increased by adding more residues. Recent papers confirm this observation; Madari *et al.* (2005) showed that NT with residue cover had higher aggregate stability, higher aggregate size values and total organic carbon in soil aggregates than TT in Brazil; Roldan *et al.* (2003) showed that after 5 years of NT maize in Mexico, soil wet aggregate stability had increased over conventional tillage (TT) as had soil enzymes, soil organic carbon (SOC) and microbial biomass (MBM). They conclude that NT is a sustainable technology.

A cover crop and the resulting mulch or previous crop residue help reduce weed infestation through competition and not allowing weed seeds the light often needed for germination. There is also evidence of allelopathic properties of cereal residues in respect to inhibiting surface weed seed germination (Steinsiek *et al.* 1982; Lodhi & Malik 1987; Jung *et al.* 2004). Weeds will be controlled when the cover crop is cut, rolled flat or killed. Farming practice that maintains soil micro-organisms and microbial activity can also lead to weed suppression by the biological agents (Kennedy 1999).

Cover crops contribute to the accumulation of organic matter in the surface soil horizon (Roldan *et al.* 2003; Alvear *et al.* 2005; Diekow *et al.* 2005; Madari *et al.* 2005; Riley *et al.* 2005), and this effect is increased when combined with NT. Mulch also helps with recycling of nutrients, especially when legume cover crops are used, through the association with below-ground biological agents and by providing food for microbial populations. Greater carbon and nitrogen were reported under no-tillage and CT compared with ploughing (TT; Campbell *et al.* 1995, 1996a,b). Others have shown that this is restricted to the surface horizons, and that the reverse occurs at greater depths in humid soils of eastern Canada (Angers *et al.* 1997). Schultz (1988) showed that C and N declined by 6% with burning but increased by 1% with stubble retention. Vagen *et al.* (2005) concluded that the largest potential for increasing SOC is through the establishment of natural or improved fallow systems (agroforestry) with attainable C accumulation rates from 0.1 to 5.3 Mg C ha⁻¹ yr⁻¹. They continue to say that in cropland, addition of crop residues or manure in combination with NT can yield attainable C accumulation rates up to 0.36 Mg C ha⁻¹ yr⁻¹. SOC is a key indicator of soil quality and Lal (2005) calculated that increasing SOC by 1 Mg ha⁻¹ yr⁻¹ can increase food grain production by 32 million Mg yr⁻¹ in developing countries. Heenan *et al.* (2004) in Australia showed that changes in SOC at the surface ranged from a loss of 8.2 t ha⁻¹ for continuous tilled cereals and residues burnt to a gain of 3.8 t ha⁻¹ where stubble was retained and soil no-tilled. Nitrogen content followed similar trends. If

the rotation included a legume, SOC accumulation was the highest.

Soil microbial biomass (SMB) has commonly been used to assess below-ground microbial activity and is a sink and source for plant nutrients. Amendments such as residues and manures promote while burning and removal of residues decrease SMB (Doran 1980; Collins *et al.* 1992; Angers *et al.* 1993*a,b*; Heenan *et al.* 2004; Alvear *et al.* 2005). Balota *et al.* (2004) in Brazil in a 20-year experiment showed that residue retention and NT increased total C by 45% and SMB by 83% at 0–50 cm depth compared with TT. Soon & Arshad (2005) showed that SMB was greater with NT than TT by 7–36%; frequent tillage resulted in a decrease in both total and active MBC. Increased SMB occurs rapidly in a few years following conversion to reduced tillage (Ananyeva *et al.* 1999; Alvarez & Alvarez 2000). Increased MBM increased soil aggregate formation, increased nutrient cycling through slow release of organically stored nutrients and also assisted in pathogen control (Carpenter-Boggs *et al.* 2003).

Cover crops help promote biological soil tillage through their rooting; the surface mulch provides food, nutrients and energy for earthworms, arthropods and micro-organisms below ground that also biologically till soils. Use of deep-rooted cover crops and biological agents (earthworms, etc.) can also help to relieve compaction under zero-tillage systems. There is a lot of literature that looks at the effects of burning, incorporation and removal of crop residues on soil properties, and much less where mulch is left on the surface. An early paper by McCalla (1958) showed that bacteria, actinomycetes, fungi, earthworms and nematodes were higher in residue-mulched fields than those where the residues were incorporated. More recent studies also show more soil fauna in no-tillage, residue-retained management treatments compared with tillage plots (Kemper & Derpsch 1981; Nuutinen 1992; Hartley *et al.* 1994; Karlen *et al.* 1994; Buckerfield & Webster 1996; Clapperton 2003; Birkas *et al.* 2004; Riley *et al.* 2005). Tillage disrupts and impairs soil pore networks including those of mycorrhizal hyphae, an important component for phosphorus availability in some soils (Evans & Miller 1990; McGonigle & Miller 1996). Zero-tillage thus results in a better balance of microbes and other organisms and a healthier soil.

Ground cover promotes an increase in biological diversity not only below ground but also above ground; the number of beneficial insects was higher where there was ground cover and mulch (Kendall *et al.* 1995; Jaipal *et al.* 2002), and these help keep insect pests in check.

Interactions between root systems and rhizobacteria affect crop health, yield and soil quality. Release of exudates by plants activate and sustain specific rhizobacterial communities that enhance nutrient cycling, nitrogen fixing, biocontrol of plant pathogens, plant disease resistance and plant growth stimulation. Sturz & Christie (2003) gave a review of this topic. Ground cover would be expected to increase biological diversity and increase these beneficial effects.

(b) *Minimal soil disturbance*

Many of the benefits of minimal soil disturbance were mentioned in the above section on permanent soil cover,

and, in fact, combining these two practices is important for obtaining the best results. The following comparisons between tillage and zero-tillage systems are made to highlight some other benefits not mentioned above.

Tractors consume large quantities of fossil fuels that add to costs while also emitting greenhouse gases (mostly CO₂) and contributing to global warming when used for ploughing (Grace *et al.* 2003). Animal-based tillage systems are also expensive since farmers have to maintain and feed a pair of animals for a year for this purpose. Animals also emit methane, a greenhouse gas 21 times more potent for global warming than carbon dioxide (Grace *et al.* 2003). Zero-tillage reduces these costs and emissions. Farmer surveys in Pakistan and India show that zero-till of wheat after rice reduces costs of production by US\$60 per hectare mostly due to less fuel (60–80 l ha⁻¹) and labour (Hobbs & Gupta 2004).

Tillage takes valuable time that could be used for other useful farming activities or employment. Zero-tillage minimizes time for establishing a crop. The time required for tillage can also delay timely planting of crops, with subsequent reductions in yield potential (Hobbs & Gupta 2003). By reducing turnaround time to a minimum, zero-tillage can get crops planted on time, and thus increase yields without greater input cost. Turnaround time in this rice–wheat system from rice to wheat varies from 2 to 45 days, since 2–12 passes of a plough are used by farmers to get a good seedbed (Hobbs & Gupta 2003). With zero-till wheat this time is reduced to just 1 day.

Tillage and current agricultural practices result in the decline of soil organic matter due to increased oxidation over time, leading to soil degradation, loss of soil biological fertility and resilience (Lal 1994). Although this SOM mineralization liberates nitrogen and can lead to improved yields over the short term, there is always some mineralization of nutrients and loss by leaching into deeper soil layers. This is particularly significant in the tropics where organic matter reduction is processed more quickly, with low soil carbon levels resulting only after one or two decades of intensive soil tillage. Zero-tillage, on the other hand, combined with permanent soil cover, has been shown to result in a build-up of organic carbon in the surface layers (Campbell *et al.* 1996*a*; Lal 2005). No-tillage minimizes SOM losses and is a promising strategy to maintain or even increase soil C and N stocks (Bayer *et al.* 2000).

Although tillage does afford some relief from compaction, it is itself a major cause of compaction, especially when repeated passes of a tractor are made to prepare the seedbed or to maintain a clean fallow. Zero-tillage reduces dramatically the number of passes over the land and thus compaction. However, natural compaction mechanisms and the one pass of a tractor-mounted zero-till drill will also result in compaction. The FAO CA web site now includes ‘controlling in-field traffic’ as a component of CA; this is accomplished by having field traffic follow permanent tracks. This can also be accomplished using a ridge-till or permanent bed planting system rather than planting on the flat (Sayre & Hobbs 2004). Some farmers feel that sub-soiling or chiselling may be needed to resolve

below-ground compaction layers before embarking on a NT strategy, especially in drier areas.

Higher bulk densities and penetration resistance have been reported under zero-tillage compared with tillage (Gantzer & Blake 1978) and are described as natural for zero-tillage. This problem is greater in soils with low-stability soil aggregates (Ehlers *et al.* 1983). Bautista *et al.* (1996) working in a semi-arid ecosystem found that zero-tillage plus mulch reduced bulk density (BD). The use of zero-till using a permanent residue cover, even when BD was higher, resulted in higher infiltration of water in NT systems (Shaver *et al.* 2002; Sayre & Hobbs 2004). Scientists hypothesized that continued use of reduced, shallow and zero-tillage would require a shift to short-term TT to correct soil problems. However, Logsdon & Karlen (2004) showed that BD is not a useful indicator and confirm that farmers need not worry about increased compaction when changing from TT to NT on deep loess soils in USA. Fabrizzi *et al.* (2005) also showed higher BD and penetration resistance in NT experiments in Argentina, but the values were below thresholds that could affect crop growth; wheat yields were the same as in the tilled treatments. This experiment left residues on the surface in NT. The authors concluded that the experiment had a short time frame and more time was needed to assess the effect on BD.

The role of tillage on soil diseases is discussed by Leake (2003) with examples of the various diseases affected by tillage. He concluded that the role of tillage on diseases is unclear and acknowledges that a healthy soil with high microbial diversity does play a role by being antagonistic to soil pathogens. He also suggested that NT farmers need to adjust management to control diseases through sowing date, rotation and resistant cultivars to help shift the advantage from the disease to the crop. A list of the impacts of minimum tillage on specific crops and their associated pathogens can be found in Sturz *et al.* (1997).

An added economic consideration is that tillage results in more wear and tear on machinery and higher maintenance costs for tractors than under zero-tillage systems.

(c) Rotations

Crop rotation is an agricultural management tool with ancient origins. Howard (1996) reviewed the cultural control of plant diseases from an historical view and included examples of disease control through rotation. The rotation of different crops with different rooting patterns combined with minimal soil disturbance in zero-till systems promotes a more extensive network of root channels and macropores in the soil. This helps in water infiltration to deeper depths. Because rotations increase microbial diversity, the risk of pests and disease outbreaks from pathogenic organisms is reduced, since the biological diversity helps keep pathogenic organisms in check (Leake 2003). The discussion of the benefits of rotations will be handled in other chapters of this publication.

Integrated pest management (IPM) should also be added to the CA set of recommendations, since if one of the requirements is to promote soil biological activity, minimal use of toxic pesticides and use of alternative pest control methods that do not affect

these critical soil organisms are needed. A review of IPM in CA can be found in Leake (2003).

5. EQUIPMENT FOR CONSERVATION AGRICULTURE

Before going on to describe a couple of case studies from Asia and Mexico, there is a need to discuss the critical importance of equipment for success with CA; zero-till and CA are bound to fail if suitable equipment is not available to drill seed into residues at the proper depth for good germination. It is urgent that CA equipment is perfected, available and adopted for this new farming system. Iqbal *et al.* (2005) studied NT under dryland conditions in Pakistan and showed that NT gave lower yields than TT, but the experiment was planted with improper equipment and with no mention of residue management; the results are therefore suspect.

There are some excellent reviews of the equipment needs for zero-tillage systems. Baker *et al.* (2002, 2006) devoted an entire book to this topic. A book on CA ('Environment, farmer experiences, innovations and socio-economic policy') edited by Garcia-Torres *et al.* (2003) has several papers on equipment for small- and large-scale farmers. The main requirements of equipment in a CA system are a way to handle loose straw (cutting or moving aside), seed and fertilizer placement, furrow closing and seed/soil compaction. There is also a need for small-scale farmers to adapt direct-drill seeding equipment to manual, animal or small tractor power sources (reduced weight and draft requirements) and reduce costs, so equipment is affordable by farmers, although use of rental and service providers allows small-scale farmers to use this system even if they do not own a tractor or a seeder.

A simple three-row small grain seeder has been developed for small-scale animal-powered farmers in Bolivia (Wall *et al.* 2003). This equipment uses a shovel rather than a disc opener to save weight. It has straw wheels attached to the coulter to help move residues aside and reduce clogging. It also has the benefit that it can be used in ploughed or unploughed soil. The main benefit farmers mentioned about this drill was savings in time; it takes 10 h to plant a hectare with this machinery and 12 days for the TT and seeding method. The conventional system also required the farmer to walk 100 km ha⁻¹ to undertake all the tillage and seeding with his animals. The stand with the new drill was 246 ± 37 plants m⁻² compared with 166 ± 39 for the conventional system. The cost of the drill was only \$330–390 in Bolivia. Similar information was provided by Ribeiro (2003) for planters in Brazil. These can be manually applied jabber planters to animal-drawn planters. In both countries, the participation of farmers, local manufacturers and extensionists was vital for success.

Saxton & Morrison (2003) looked at equipment needs for large-scale farmers where tractor horsepower, weight and draft are less important. Earlier machines were developed for clean tilled farm fields, whereas new NT machines provide precision seed placement through consistent soil penetration and depth and also supply fertilizer in bands which is crucial for minimizing nutrient losses in zero-till systems. This paper discusses

the use of disc openers versus hoe and chisel openers and the use of additional straw and chaff spreading devices.

6. CASE STUDY FROM THE RICE–WHEAT SYSTEMS OF SOUTH ASIA

(a) Case study from Asia

The first case study looks at the 13.5 Mha of the rice–wheat systems of the Indo-Gangetic Plains for South Asia (RWC web site: <http://www.rwc.cgiar.org/RWC-Crop.asp>). The traditional cultivation technique used for growing rice in this system, and also in much of the rice growing regions of Asia, is wet ploughing of soils in the main rice field (puddling), followed by transplantation of rice seedlings grown in separate seedbeds. Interestingly, this system of rice cultivation is often cited as being used for centuries without declining productivity. However, it was at relatively low subsistence rice yield levels. There are several excellent reviews of a number of Asian long-term experiments using modern varieties on this issue, some rice–wheat and others rice–rice, with some showing yield declines while others do not (Cassman *et al.* 1995; Abrol *et al.* 1997; Dawe *et al.* 2000).

Puddling was done by farmers over the centuries for very specific reasons, the most important being to help control weeds; farmers found that keeping soils anaerobic and flooded reduced weed problems and also hand weeding was easier with these softened soils. The puddling essentially reduced water percolation and infiltration and ponded the water on the surface. Less is written on the puddling effect on soil biological properties although some work is available from research done at IRRI in the 1990s (Reichardt *et al.* 1997, 2001). The authors conclude that SMB plays a significant role as a passive nutrient pool and suggests that its reduction, found in puddled soils in the second half of the cropping season, could be a mechanism that contributes to declining productivity in continuous rice cropping systems. Little has been published on soil microbes in rice–wheat systems.

When modern varieties of wheat and rice were introduced to South Asia in the 1960s, farmers in Northwest India and Pakistan introduced rice into their wheat systems and farmers in the eastern side of South Asia introduced wheat into their rice systems; wheat was grown in the cool dry season and rice in the warm wet monsoon months. This intensified the system that has grown to 13.5 Mha since the 1960s. It is now one of the most important cropping systems for food security in South Asia along with rice–rice systems. One of the main issues that confronted farmers when this new system was introduced and found feasible and profitable was the soil physical properties left after harvest of a puddled transplanted rice crop. The effect of puddling reduced soil structure, especially stable soil aggregates, and led to formation of compaction layers (Hobbs *et al.* 1993). Soil cracking was higher under intensive puddling (Mohanty *et al.* 2004). Unpuddled direct-seeded rice maintained the soil in a better physical condition, although yields were lower where weeds were not controlled. Farmers ploughed their fields many times to obtain a suitable seedbed for planting wheat (Hobbs & Gupta 2003, table 7.1). This ploughing takes time and often results in late planting

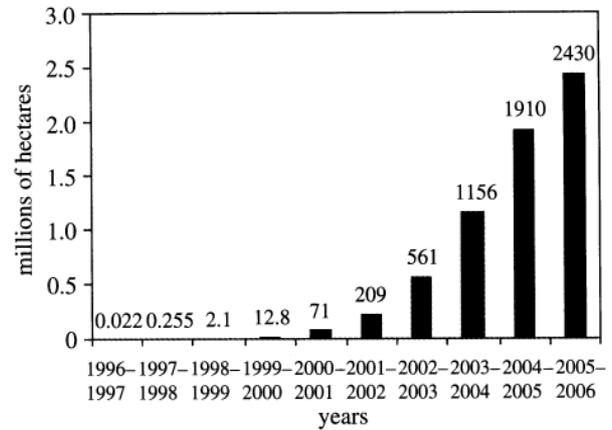


Figure 1. Estimated area growth of no-till wheat in the Indo-Gangetic Plains for the past 10 years (adapted from Rice–Wheat Consortium (RWC) for the Indo-Gangetic Plains (2006). <http://www.rwc.cgiar.org>).

and decline in wheat yield potential, plus many other negative effects (Hobbs & Gupta 2003, 2004).

The solution for late planting and problems of delayed turnaround from rice harvest to wheat planting came from the introduction of zero-tilled wheat into rice stubbles that started in the region in the mid-1980s. Efforts to adapt and promote resource conserving technologies (RCTs that include NT) in the Indo-Gangetic Plains (IGP) have been underway for nearly three decades, but it is only in the past 4–5 years that the technologies are finding accelerated acceptance by the farmers (figure 1). The spread of NT is taking place in the irrigated RW regions but is yet to be rooted in the rainfed agro-ecoregions. In the last 2004–2005 wheat season, it was estimated that nearly 2 Mha of zero-till wheat was being grown by 425 000 farmers in the four South Asian countries (RWC Highlights 2005: http://www.rwc.cgiar.org/Pub_Info.asp?ID=152); both large- and small-scale farmers adopted this technology with small-scale farmers renting zero-till drill services from service providers. The key to this rapid adoption in the last 5 years was the use of farmer participatory approaches to allow 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; cheap, affordable, effective drills are available based on the use of the inverted T coulter technology that was introduced into India and Pakistan from New Zealand.

One major need of this system is the development and availability of equipment that will allow good germination of rice and wheat while, at the same time, minimizing soil disturbance and sowing the seed and banded fertilizer into loose and anchored stubbles. The RWC members are working vigorously in partnership with local manufacturers and farmers to make new equipment available for experimentation at an affordable price, with provisions for after-sales service and supply of needed spare parts to make this system successful. Recently, multicrop zero-till ferti-seed drills fitted with inverted T openers, disc planters, punch planters, trash movers or roto-disc openers have been developed for seeding into loose residues (RWC Highlights 2004–2005; figure 2).

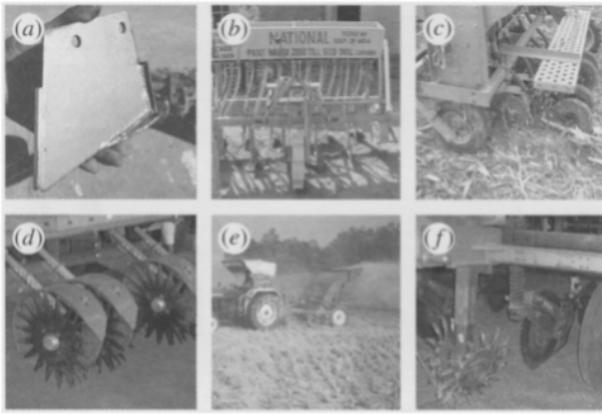


Figure 2. Various equipments for planting wheat no-till in RWC. (a) inverted T coulters, (b) Indian no-till drill using inverted T, (c) disc-type planter, (d) star-wheel punch planter, (e) 'happy planter' where straw picked up and blown behind seeder and (f) disc planter with trash mover.

Many advantages have been mentioned and characterized for this innovation including US\$145 million savings in fuel costs (2004 costs) and the benefits of less greenhouse gas emissions, less weeds, more beneficial insect activity, improved water use efficiency, and also important higher yields at less cost, improved incomes from wheat and savings in time that can be used for other productive uses (Hobbs & Gupta 2004). It is anticipated that as machinery manufacturers keep pace with demand for drills, as the message about the benefits of zero-till wheat reaches more farmers, and as farmer mindsets about the need for tillage are overcome that the acreage for this innovation will cover the bulk of the wheat planted after rice in South Asia.

However, the story does not end here. In order for the benefits of zero-tilled wheat to be seen in the entire system and for soil physical and biological health to improve and the rice-wheat system to become more sustainable, rice practices will also have to change. A move is already afoot in the rice-wheat consortium partners (national and international programmes) to research, experiment and promote a move to zero-till direct-seeded rice: a more aerobic rice system that does away with puddling of soils. These aerobic systems are based on direct-seeded rice systems on either the flat or raised beds, with and without tillage and with or without transplanting (RWC DSR paper: http://www.rwc.cgiar.org/Pub_Info.asp?ID=123). The ultimate system would allow farmers to grow zero-till rice followed by zero-till wheat. Wheat yields are best after direct-seeded rice without puddling (DSNP; Hobbs *et al.* 2002; Tripathi *et al.* 2005).

Various national and international research and breeding agencies are now exploring aerobic rice (Bouman *et al.* 2002). The main issue to resolve relates to effective weed control in a non-puddled rice system. Various innovative integrated ways are being sought to handle this problem, including use of cover crops and mulches, more competitive rice varieties against weeds and use of selective herbicides. Availability of roundup-ready transgenic rice and/or development of cultivars suited to direct seeding with zero-till drills, having early vigour and competitive with weeds, would go a long way to help resolve this issue. One encouraging

technology intercropped direct-seeded rice with a green manure (*Sesbania aculeata*). After a month, the crop is sprayed with 2,4-D herbicide to knock down the green manure and kill any germinating broadleaf weeds. The dying weeds and GM provide nutrients to the rice crops as they decompose, but new weeds are suppressed by the ground cover and allelopathic properties of the mulch. The results look good and this research will be reported soon. In addition to zero-till rice and wheat, attempts are also being made to diversify the cropping systems by introducing other crops into new rotations that help break disease and insect cycles and provide more income and diversity for farmers. This may help with some other problems that have surfaced when rice is shifted from anaerobic to aerobic systems. Widespread infestations of the root knot nematode (*Meloidyogyne graminicola*) on rice were found when direct-seeded rice was grown instead of puddled rice in Bangladesh (Padgham *et al.* 2004).

(b) Case study from Mexico

Maize-wheat cropping patterns are common in the irrigated northwest areas of Mexico and the rainfed areas of the altiplano areas of central Mexico. In both situations, the major limiting factor is moisture. This case study introduces the concept of permanent bed systems for addressing efficient use of water. In bed systems, soil is raised in a ridge-and-furrow configuration. These bed systems involved tillage to prepare the soil before making the beds. However, many traditional bed planting systems did not receive tillage; the *chinampas* of pre-Colombian Mexico and the *waru warus* of Peru and Bolivia used crop residue mulching or only superficial tillage (Thurston 1992). Bed systems reduce compaction in the rooting zone by confining wheel traffic to the furrow bottoms. The case study described here from Mexico looks at the results of using a permanent bed planting maize-wheat system where soil disturbance is minimized, crop residues are retained on the surface from previous crops and reshaping of beds is done only as needed between crop cycles (Limon-Ortega *et al.* 2002).

The experiment used for this paper was undertaken by the International Maize and Wheat Improvement Center (CIMMYT) in the State of Sonora in Northwest Mexico. Farmers have 225 000 hectares of irrigated land in this area with maize, sorghum, soybean, safflower, dry beans, cotton and wheat, the major crops. Ninety-five per cent of the farmers now grow crops on beds with farmers changing from the conventional planting on the flat with basin irrigation in the last 20 years (Aquino 1998). This change was a result of water shortages from the water storage reservoir system; farmers had to find more efficient water use systems in order to expand acreage. Results suggest that bed planted systems need 29% less water than flat planting systems for an 8% higher yield (Sayre & Hobbs 2004). Most of the farmers still use TT to remake the beds for each new crop, but results that are reported below suggest that use of permanent bed systems where tillage is minimized and crop residues are left on the surface will be more sustainable.

The treatments in this long-term trial were as follows.

- (i) CT with formation of new beds for each crop and with all the crop residues incorporated.
- (ii) Permanent beds with all the residues burned.
- (iii) Permanent beds with 30% of the residues retained on the surface and the rest baled for fodder.
- (iv) Permanent beds with the maize residue baled for fodder and the wheat residue retained.
- (v) Permanent beds with all the residues retained.

A detailed account of this experiment can be found in Sayre & Hobbs (2004). Yield differences were small in the first 5 years supporting the idea that some transitional years are needed before changes occur in soil properties with changes in management. Changes started to appear between treatments in the sixth and subsequent years with the permanent bed treatment with all the residues retained the best and highest yielding plot, and the permanent bed treatment with residues burnt the worst and lowest yielding plot. The treatment with CT with residues incorporated was statistically at par with the best permanent bed system but incurred higher costs for land preparation.

Organic matter, nitrogen levels, surface soil aggregate size and SMB were higher in the permanent beds with residue retention. One valuable insight from this experiment was the lower soil strength/compaction in all treatments, except the one where residues were burned. The addition of the residue plays a significant role in reducing compaction at the soil surface and increasing water infiltration in minimal tilled plots. Similar data confirmed this finding in a similar maize-wheat long-term experiment under rainfed conditions in the altiplano areas near Mexico City (Govaerts *et al.* 2005). In this rainfed experiment, zero-tilled plots with residue retention resulted in higher and more stable yields than conventionally tilled plots with residues incorporated. Zero-tilled plots without residue retention had much reduced yields. In the same experiment, permanent raised beds combined with rotation and residue retention yielded the same as zero-tilled plots with residue retention. The bed system gave farmers an added advantage of being able to use more varied weed and fertilizer practices.

Larger-scale demonstrations have been planted on farmer's fields. The permanent beds averaged 7.2 t ha^{-1} compared with 6.2 t ha^{-1} for the conventionally made beds. The data also show that average returns over variable costs increased by 75% for the permanent bed system with residue retention compared with the conventional tilled treatment. The importance of suitable equipment that will allow seeding of crops into permanent beds with residue retention cannot be overemphasized. Systems based on discs, punch planters and strip tillage are being experimented with in Mexico and South Asia (Sayre & Hobbs 2004).

7. CLIMATE CHANGE AND CONSERVATION AGRICULTURE

Lal (2005) suggested that by adopting improved management practices on agricultural land (use of NT and crop residues), food security would not only be enhanced but also offset fossil fuel emissions at the rate

of 0.5 Pg C yr^{-1} . Climate change is likely to strongly affect rice-wheat, rice-rice and maize-based cropping systems that, today, account for more than 80% of the total cereals grown on more than 100 Mha of agricultural lands in South Asia. Global warming may be beneficial in some regions, but harmful in those regions where optimal temperatures already exist; an example would be the rice-wheat mega-environments in the IGP that account for 15% of global wheat production. Agronomic and crop management practices have to aim at reducing CO_2 and other greenhouse gas emissions by reducing tillage and residue burning and improving nitrogen use efficiency. In the IGP, resource-conserving technologies continue to expand in the rice-wheat cropping systems and save 50–60 l of diesel ha^{-1} plus labour, and significantly reduce release of CO_2 to the environment. Methane emissions that have a warming potential 21 times that of CO_2 are common and significant in puddled anaerobic paddy fields and also when residues are burnt. This GHG emission can be mitigated by shifting to an aerobic, direct seeded or NT rice system. A review of the other benefits of direct seeding and NT in RW areas of South Asia can be found in Grace *et al.* (2003). Nitrous oxide has 310 times the warming potential of carbon dioxide, and its emissions are affected by poor nitrogen management. Sensor-based technologies for measuring normalized differential vegetative index and moisture index have been used in Mexico and South Asia to help improve the efficiency of applied nitrogen and reduce nitrous oxide emissions.

8. CONCLUSIONS

Crop production in the next decade will have to produce more food from less land by making more efficient use of natural resources and with minimal impact on the environment. Only by doing this will food production keep pace with demand and the productivity of land be preserved for future generations. This will be a tall order for agricultural scientists, extension personnel and farmers. Use of productive but more sustainable management practices described in this paper can help resolve this problem. Crop and soil management systems that help improve soil health parameters (physical, biological and chemical) and reduce farmer costs are essential. Development of appropriate equipment to allow these systems to be successfully adopted by farmers is a prerequisite for success. Overcoming traditional mindsets about tillage by promoting farmer experimentation with this technology in a participatory way will help accelerate adoption. Encouraging donors to support this long-term applied research with sustainable funding is also an urgent requirement.

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