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The spread of Conservation Agriculture: Justification, sustainability and uptake[1]

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Conservation Agriculture (CA) has been practised for three decades and has spread widely. We estimate that there are now some 106 million ha of arable and permanent crops grown without tillage in CA systems, corresponding to an annual rate of increase globally since 1990 of 5.3 million ha. Wherever CA has been adopted it appears to have had both agricultural and environmental benefits. Yet CA represents a fundamental change in production system thinking. It has counterintuitive and often unrecognized elements that promote soil health, productive capacity and ecosystem services. The practice of CA thus requires a deeper understanding of its ecological underpinnings in order to manage its various elements for sustainable intensification, where the aim is to optimize resource use and protect or enhance ecosystem processes in space and time over the long term. For these reasons CA is knowledge-intensive. CA constitutes principles and practices that can make a major contribution to sustainable production intensification. This, the first of two papers, presents the justification for CA as a system capable of building sustainability into agricultural production systems. It discusses some of CA's major achievable benefits, and presents an overview of the uptake of CA worldwide to 2009. The related paper elaborates the necessary conditions for the spread of CA.

Keywords: Conservation Agriculture, conservation tillage, no-till, soil health, sustainability, technology adoption, tillage practices

Introduction

The challenge of agricultural sustainability has become more intense in recent years with the sharp rise in the cost of food and energy, climate change, water scarcity, degradation of ecosystem services and biodiversity, and the financial crisis. The expected increase in population and the associated demands for food, water and other agricultural products will bring additional pressures. In recent decades, the development community including politicians, policy makers, institutional leaders as well as academics, scientists and extension workers have been highlighting the need for the development of sustainable agricultural systems. In response to this, action has been promoted at all levels and yet, as witnessed in the Millennium Ecosystem Assessment (MEA, 2005), the World Development Report 2008 (WDR, 2008) and the IAASTD reports (McIntyre *et al.*, 2008), some agricultural systems are still being promoted with unacceptably high environmental, economic and social costs, albeit with the promise of gains

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in output. Consequently, business-as-usual with regards to agricultural development is increasingly considered inadequate to deliver sustainable production intensification to meet future needs (Shaxson, 2006).

Conservation Agriculture (CA) is being increasingly promoted as constituting a set of principles and practices that can make a contribution to sustainable production intensification (FAO, 2008; Pretty, 2008) because it addresses missing components in the intensive tillage-based standardized seed-fertilizer-pesticide approach to agriculture intensification.

This first of two papers describes CA within the context of a typology of tillage practices and presents the justification for CA as a system of principles and practices capable of building sustainability into production systems. It then discusses some of CA's major achievable benefits, and presents an overview of the uptake or adoption of CA worldwide. A second paper (Kassam *et al.*, 2010) presents an elaboration of some of the necessary conditions for the spread of CA.

The underpinnings of plant production, environmental resilience and agricultural sustainability

The principles of Conservation Agriculture

The main criterion for conservation-effective agricultural systems is the provision of an optimum environment in the root-zone to maximum possible depth. Roots are thus able to function effectively and without restrictions to capture plant nutrients and water. Water thus enters the soil so that (a) plants never, or for the shortest time possible, suffer water stress that would limit the expression of their potential growth; and so that (b) residual water passes down to groundwater and stream flow, not over the surface as runoff. Beneficial biological activity, including that of plant roots, thus occurs in the soil where it maintains and rebuilds soil architecture, competes with potential in-soil pathogens, contributes to soil organic matter and various grades of humus, and contributes to capture, retention, chelation and slow release of plant nutrients. Thus, 'conservation-effectiveness' encompasses not only conserving soil and water, but also the biotic bases of sustainability.

The key feature of a sustainable soil ecosystem is the biotic actions on organic matter in suitably porous soil (Flaig *et al.*, 1977). This means that, under CA, soils become potentially self-sustainable. In CA systems with the above attributes there are many similarities to resilient 'forest floor' conditions (Blank, 2008):

- Organic materials are added both as leaf and stem residues from above the surface and as root residues beneath the surface where the soil biota are active and carbon is accumulated in the soil.
- Carbon, plant nutrients and water are recycled.
- Rainwater enters the soil complex readily, since rates of infiltration (maintained by surface protection and varied soil porosity) usually exceed the rates of rainfall.

Soil organic matter is neither just a provider of plant nutrients nor just an absorber of water (Flaig *et al.*, 1977). The combined living and non-living fractions together form a key part of the dynamics of soil formation, resilience and self-sustainability of CA systems. In the functioning of soil as a rooting environment, the integrated effects of the physical, chemical and hydrological components of soil productive capacity are effectively 'activated' by the fourth, the biological component. This variously provides metabolic functions, acting on the non-living organic materials (Wood, 1995; Doran & Zeiss, 2000; Lavelle & Spain, 2001; Coleman *et al.*, 2004; Uphoff *et al.*, 2006) to:

- Retain potential plant-nutrient ions within their own cells, with liberation on their death, acting as one form of slow-release mechanism; mycorrhizae and rhizobia, as well as free-living N-fixing bacteria, make nutrients available to plants in symbiotic arrangements.
- Break down and transform the complex molecules of varied dead organic matter into different substances, both labile and resistant, according to the composition of the substrate.
- Leave behind transformed materials with differing degrees of resistance to subsequent breakdown by biotic process of other soil organisms. Over the long term, this leaves some residues less changed than others, providing long-lasting and slowly released remnant reserves of the

nutrient and carbonaceous materials of which they were composed.

- Produce organic acids which, by leaching, contribute to soil formation from the surface downwards by acting to break down mineral particles as part of the soil 'weathering' process. Organic acids also help with transporting lime into the soil profile and mobilizing nutrients like phosphates.
- Provide organic molecules as transformation products which contribute markedly to soil's CEC; this also augments the soil's buffering capacity to pH changes and to excesses or deficiencies of nutrient ions available to plants.
- Provide humic gums which, together with fungal hyphae and clay bonds, make for different sizes of rough-surfaced aggregates of individual soil particles that in turn provide the permeability of the soil in a broad distribution of pore sizes.
- Increase the burrowing activities of meso-organisms such as earthworms, and of roots (leaving tubes after they have died and been decomposed).

The key components of optimum Conservation Agriculture

The three components of optimum CA are:

(1) Maintaining year-round organic matter cover over the soil, including specially introduced cover crops and intercrops and/or the mulch provided by retained residues from the previous crop;
(2) Minimizing soil disturbance by tillage and thus seeding directly into untilled soil, eliminating tillage altogether once the soil has been brought to good condition, and keeping soil disturbance from cultural operations to the minimum possible;
(3) Diversifying crop rotations, sequences and associations, adapted to local environmental conditions, and including appropriate nitrogen-fixing legumes; such rotations contribute to maintaining biodiversity above and in the soil, contribute nitrogen to the soil/plant system, and help avoid build-up of pest populations.

The soil capacity to favour root growth and water transmission is maintained through the activity of soil organisms sufficiently provisioned with organic matter, water and nutrients. A consequence of their activity is soil aggregation interspersed with voids (pores), depending on organisms' production of roots, exudates, gums, hyphae and on their proliferative burrowing and distributive activities. Multiple attributes of organic matter in soil – dynamized by the soil biota – therefore make it a key factor for improving and maintaining yields (of plants and of water). Management actions which increase/optimize organic matter content of soils tend to be beneficial; those that result in depletion of organic matter content tend to be detrimental.

Tillage tends to engender accelerated oxidative breakdown of organic matter with accelerated release of increased volumes of CO_2 to the atmosphere, beyond those from normal soil respiration processes. Combining the retention of crop residues (rather than export or burning off) with direct seeding of crops without 'normal' tillage leads to retention and increase of organic matter, as a substrate for the activity of soil biota and for the soil's capacities to retain carbon, and to better provide water and nutrients to plant roots 'on demand' over sustained periods. The relationship between components of CA and desired soil conditions are listed in Table 1 (Friedrich *et al.*, 2009).

Tillage has long been used by farmers to loosen soil, make a seedbed and control weeds. But not all outcomes are positive, especially when considered over long timescales. Wheels, implements and even feet can compact soil. Too-frequent (and/or too-severe) tillage results in disruption of the aggregates making up a soil's biologically induced architecture. Since the sustainability of a soil's productive capacity depends on the influence of the soil biota on soil-crumb/aggregate re-formation, the soil aerating effects of undue tillage can accelerate the rate of biotic activity and the consequent more-rapid oxidation of their substrate organic matter. If the mean rate of soil's physical degradation exceeds the mean rate of its recuperation due to the soil biota, its penetrability by water, roots and respiration gases diminishes, productivity declines, and runoff and erosion ensue. The soils which are most vulnerable to tillage-stimulated rapid loss of soil organic matter are those of coarse texture and where the clay fraction is dominated by low-activity clays. Such soils (e.g., ferralsols, cambisols) are widely distributed in the tropics and subtropics, and total over

Table 1 Effects of CA components fully applied together

CA component ► ***To achieve ▼***	***Mulch cover (crop residues, cover-crops, green manures)***	***No tillage (minimal or no soil disturbance)***	***Legumes (as crops for fixing nitrogen and supplying plant nutrients)***	***Crop rotation (for several beneficial purposes)***
Simulate 'forest floor' conditions	√	√		
Reduce evaporative loss of moisture from soil surface	√			
Reduce evaporative loss from upper soil layers	√	√		
Minimize oxidation of soil organic matter, CO_2 loss		√		
Minimize compaction by intense rainfall, passage of feet and machinery	√			
Minimize temperature fluctuations at soil surface	√			
Maintain supply of organic matter as substrate for soil biota	√			
Increase and maintain nitrogen levels in root-zone	√	√	√	√
Increase CEC of root-zone	√	√	√	√
Maximize rain infiltration; minimize runoff	√	√		
Minimize soil loss in runoff or wind	√	√		
Maintain natural layering of soil horizons by actions of soil biota	√	√		
Minimize weeds	√	√		√
Increase rate of biomass production	√	√	√	√
Speed soil porosity recuperation by soil biota	√	√	√	√
Reduce labour input		√		
Reduce fuel-energy input		√		
Recycle nutrients	√	√	√	√
Reduce pests and diseases				√
Rebuild damaged soil conditions and dynamics	√	√	√	√

Source: Friedrich *et al.*, 2009.

750 million ha (FAO, 1978–1981; Higgins & Kassam, 1981).

A typology of terms

Tillage or conventional tillage generally refers to inversion ploughing of topsoil to at least 20 cm or more. Several terms have been coined to reflect non-plough-based tillage practices in production systems. Some of these production systems may have soil organic cover from crop residues of previous crops and from cover crops, some may be based on mono-cropping, and others may include crop rotations and associations with legumes and non-legumes including deep-rooting annual crops and trees.

We provide a description of different types of tillage practices and associated terms in Table 2. This typology illustrates the various tillage terms used and the relative severity of tillage associated with different tillage practices from the most severe soil disturbance in the case of Tillage Agriculture (Terms 1, 1a, 1b, 1c in Table 2) to least severe soil disturbance in the case of Conservation Agriculture (Terms 3, 3a, 3b), with Conservation Tillage being somewhere in between (Terms 2, 2a, 2b). In Italy, Agricolturu Blu (or Blue Agriculture) is the term used synonymously with CA (Pisante, 2007), and in francophone areas the term Direct seeded mulch-based cropping system (DMC) is used to describe a family of practices known as CA (Seguy *et al.*, 2006a,b, 2008). The term CA was adopted during the First World Congress on Conservation Agriculture, Madrid 2001 (organized by FAO and the European CA Federation: see http://www.fao.org/ag/ca).

Farmers across the world in different agro-ecological and socio-economic situations adopt a range of strategies in order to approximate to these optimum conditions. Therefore a typology of tillage practices in production systems needs primarily to be based on the methods used (Table 2) and the outcomes the practices employed have on the way soils react, with respect to improvement in productivity *and* sustainability simultaneously for the provision of plants and water on a regular recurrent basis, which is considered in the next section.

Table 3 provides a ranking of agricultural systems according to effectiveness of conservation of soils' capacities to yield plants and water on a sustainable basis, based on the similarities and differences among practices in terms of the key characteristics of CA: no soil disturbance (stirring); direct seeding, permanent soil cover with plant organic matter; crop rotations and associations including legumes.

Such types of information from soils in good condition under CA provide a range of yardsticks against which to compare the benefits of CA and the health of the soil with the damages caused by 'conventional' tillage agriculture, as discussed below.

Organic agriculture, agroforestry and shifting agriculture are included in Table 3 in addition to the three production systems described in Table 1 because CA has many features in common with these systems, although organic farming does not permit the use of synthetic materials such as mineral fertilizers. Where organic farming is tillage-based, application of the three CA principles and associated practices would enhance productivity and resilience of organic production systems and offer the economic and environmental benefits that have been described earlier. Indeed, one future opportunity that may be harnessed is the integration of compatible CA practices into organic farming. CA-based organic farming would lead to greater soil health and productivity, increased efficiency of use of organic matter, and reduction in use of energy. Organic CA farming is already practised in the USA, Brazil and Germany.

Agroforestry systems involve the growing of woody perennials and annual crops together in a sustainable manner in most ecologies, and it is increasingly practised in degraded areas with perennial legumes. The practice brings environmental benefits through soil protection and efficiency of utilization of water and soil nutrients. It also creates a wider diversity of environments for wildlife and other fauna. Local knowledge concerning utility of native species could be mixed with scientific information to develop future agroforestry farming systems. A particular advantage of CA in agroforestry systems is the better compatibility with tree and field crops since the tree roots cannot be caught by ploughs or deeper reaching tillage implements. CA works well for agroforestry and related systems in which crops are combined with woody perennials in the production system. This is particularly because the minimal or no soil

Table 2 Typology of terms describing tillage practices in production systems[a]

Terms	***Description/comments***
[1] Tillage Agriculture	Farming based on intensive mechanical tillage involving soil inversion and harrowing, and high soil disturbance. Conventional 'arable' agriculture is normally based on soil tillage as the main operation. The most widely known tool for this operation is the plough, which has become a symbol of agriculture. Soil tillage has in the past been associated with increased fertility, which originated from the mineralization of soil nutrients as a consequence of soil tillage. This process leads in the long term to a reduction of soil organic matter through its accelerated oxidation by soil organisms. Soil organic matter not only provides nutrients for the crop but is also, above all else, a crucial element for the stabilization of soil structure. Therefore, most soils degrade under prolonged intensive arable agriculture. This structural degradation of the soils results in the formation of crusts and compaction and leads in the end to soil erosion. The process is dramatic under tropical climatic situations but can be noticed all over the world. Mechanization of soil tillage, allowing higher working depths and speeds and the use of certain implements like ploughs, disk harrows and rotary cultivators, has particularly detrimental effects on size, arrangement and stability of soil structural units/ 'soil crumbs'.
[1a] Tillage, intensive tillage, conventional tillage	Tillage is a generic term and is used broadly. Tillage embraces all soil operations using plough, harrow and other farm tools or mechanical implements for seedbed preparation that aim at creating soil and environmental conditions for seed germination, seedling establishment and crop growth. It includes mechanical methods based on conventional techniques of ploughing and harrowing. Intensive tillage systems leave little crop residue cover on the soil. These types of tillage systems are often referred to as conventional tillage systems. These systems involve often multiple operations with implements such as a mouldboard plough, disk plough, chisel plough, rotary tiller, subsoiler, ridge or bed-forming tillers. Then a finisher with a harrow, rolling basket and cutter can be used to prepare the seedbed; there are many variations. It may be taken to include the use of hand-held tillage implements, as found on many smallholder farms.
[1b] Plough-till	Refers to mechanical soil manipulation of an entire field, and involves mouldboard or disk ploughing followed by one or two harrowings. Plough-till embraces primary cultivation based on ploughing with soil inversion, secondary cultivation using disks or cultivators, and tertiary working by cultivators and harrows. These tools are often drawn by animals or by tractors and other mechanically powered devices. The mechanical soil disturbance involved increases the risk of erosion. Ploughing removes the vegetation cover and exposes the soil to rainfall, wind and overland flow. It also encourages accelerated rates of oxidation of soil organic matter and consequently of carbon dioxide to the atmosphere. The technique gives a weed-free seedbed, incorporates fertilizer and improves soil conditions. The effects of tillage methods on soil properties and on the erosion risk are hard to generalize. The effects vary depending on basic soil properties. For example, where the soil has favourable structure with a high proportion of water-stable aggregates, and is permeable, mechanical soil disturbance is likely to increase the risks of soil erosion. On the other hand, where the soil has a smooth crusted surface and compacted subsoil horizons, a massive non-porous, unstable structure, carefully judged, timely mechanical tillage is likely to decrease the risks of soil erosion, usually only temporarily.

(*Continued*)

Table 2 *Continued*

Terms	***Description/comments***
[1c] Minimum-till or minimum tillage	The term minimum-till has caused the greatest confusion because the minimum cultivation required to grow a crop successfully varies from zero to a complete range of primary and secondary tillage operations depending on soil properties and crops. It is commonly defined as 'the minimum soil manipulation necessary for crop production or meeting tillage requirements under the existing soil and climatic conditions'. It often means any system that has few tillage requirements. It may also mean tillage of only part of the land, e.g. strip tillage or zonal tillage. It is mainly done to reduce cost and hence it is also sometimes understood as the combination of several tillage operations in one implement.
[2] Conservation Tillage (CT)	The origin of CT is the attempt to reduce soil erosion. The classical definition of CT is any tillage operation which leaves a minimum of 30% of the soil surface covered with crop residues. This results in planting or sowing through the previous crop's residues that are purposely left on the soil surface. The primary aim of CT is to reduce tillage operations typically associated with intercrop soil or seedbed preparation. In strip-till (see below), which is also called 'zone tillage' or 'vertical tillage', a narrow band of soil is tilled and seeding is done directly into the loosened soil in this strip. In no-till, no intercrop tillage is used and seeding is done directly into the surface residues of previously harvested crops. The term CT has been used for varied tillage practices under a range of conditions. The vague use of the term for differing situations has created confusion and misunderstanding. The term encompasses a broad spectrum of practices ranging from no-till to intensive tillage, depending on soil conditions. CT has been defined as 'any tillage sequence that reduces the loss of soil or water relative to plough-till'; often it is a form of non-inversion tillage that retains a protective layer of mulch, and is more specifically aimed at SWC (soil and water conservation). The key techniques used for SWC are (1) residue mulches and (2) an increase in surface roughness. Increases in surface roughness can be achieved by chisel ploughing, strip tillage, ridge-furrow systems or tillage methods that cause soil inversion. If done at the right soil moisture content and with the right equipment, inversion tillage can produce an almost ideal rough seedbed. Adequate supplies of mulching materials are not always available. In such situations, CT techniques may include contour ridges, tied ridges, camber bed system, and broad bed-and-furrow systems. Some commonly used practices falling under the generic term of CT include: no-till, minimum-till, reduced tillage, mulch tillage and ridge tillage, all aiming at preserving the topsoil, and saving on fuel, labour and equipment costs. Reduced tillage is often used to describe all no-plough based cultivation practices, often but not exclusively with soil disturbance confined to soil depth of less than 15 cm. The main purpose is to leave the soil surface untouched and with this even ripping or subsoiling can qualify under CT.
[2a] Strip-till	Strip-till is a conservation system that uses a minimum of tillage. The term is used to describe a system of establishing a crop that minimizes the amount of soil disturbance and maximizes efforts to retain the integrity of crop residue on the soil surface. It combines the soil drying and warming benefits (when required) of conventional tillage with the soil-protecting advantages of no-till by disturbing only the portion of the soil that is to contain the seed row. This type of tillage is performed with special equipment and requires the farmer to make multiple trips. Each row that has been strip-tilled is usually about 8–10 inches (20–25 cm) wide. Another benefit of strip-tilling is that the farmer can apply chemicals and fertilizer at the same time as tillage. Strip-till differs from no-till/direct seeding. It normally involves a tillage operation in the autumn that clears residue in the target seed zone, places soil in a ridge to aid drying and soil warmth to facilitate seeding at a later date, and may or may not include fertilizer placement. A second operation at seeding time places seed (and usually additional fertilizer) in the ridged seed zone.

(*Continued*)

Table 2 *Continued*

Terms	***Description/comments***
[2b] No-till or No-tillage, Zero-till or Zero-tillage, No-till farming, Direct seeding	These terms often mean the same and refer to growing crops from year to year without disturbing the soil through tillage. When a crop is planted directly into a seedbed that has not been tilled since the previous seedbed it is called a no-till or no-tillage system. The term no-till is used interchangeably with the terms zero-till and direct seeding and vice versa. The maximum amount of crop residue is retained on the surface, and weeds are controlled by chemicals, by residue mulch, by using an aggressive cover crop, or by a combination of these methods. Soil-disturbing activities are limited only to those necessary to plant seeds, place nutrients and condition residues. Direct seeding describes a system of establishing a crop that minimizes the amount of soil disturbance and maximizes efforts to retain the integrity of residue on the soil surface. If soil is disturbed at harvesting, as in the case of root crops, some workers argue the system is no longer a no-till system. According to the definition given here, however, soil disturbance at harvest is allowed in a no-till system. No-till with retained crop residues increases the amount of water in the soil, decreases erosion, and increases the amount and variety of life in and on the soil. When repeated continuously, it can be developed into CA, *sensu strictu*. However, the term direct seeding is often also used for seeding into conventionally prepared soil, contrary to transplanting small plants or even to combining all tillage and the seeding operation in one pass with special equipment. Therefore the term direct seeding should be used in combination with no- or zero-tillage if it is referring to no-tillage.
[3] Conservation Agriculture (CA)	CA is a concept for resource-saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment. CA is based on enhancing natural biological processes above and below the ground. Interventions such as mechanical soil-disturbing tillage are reduced to an absolute minimum, and the use of external inputs such as agrochemicals and nutrients of mineral or organic origin are applied at an optimum level and in a way and quantity that does not interfere with, or disrupt, the biological processes. CA is characterized by three sets of principles which are linked to each other and are applied simultaneously, namely: (1) continuous minimum mechanical soil disturbance including direct seeding and no inversion tillage; (2) permanent organic soil cover with crop residue, stubble, cover crops, etc.; and (3) diversified crop rotations in the case of annual crops or plant associations in case of perennial crops. The term CA was adopted during the First World Congress on Conservation Agriculture, Madrid 2001, organized by FAO and the European Conservation Agriculture Federation. CA systems are also referred to as No-Till or Zero-Till Farming Systems when no-tillage is accompanied by direct planting of crop seeds, permanent organic soil cover and crop rotation as described above for CA. The term is quantified as follows: (1) Minimal Soil Disturbance: the disturbed area must be less than 15 cm wide or 25% of the cropped area (whichever is lower). No periodic tillage that disturbs a greater area than the aforementioned limits. (2) Soil cover: three categories are distinguished: 30–60%, 61–90% and 91+% ground cover, measured immediately after the planting operation. Ground cover less than 30% will not be considered CA. (3) Crop rotation: rotation should involve at least three different crops. However, mono-cropping is not an exclusion factor if it does not lead to pest build-up or other problems.
[3a] Agricoltura Blu (or Blue Agriculture)	This is synonymous with CA. The name Agricoltura Blu was coined by the Italian Association for an Agronomical and Conservative Land Management (AIGACoS). Blue refers to water and the environmental benefits of CA.

(*Continued*)

Table 2 *Continued*

Terms	*Description/comments*
[3b] Direct seeding mulch-based cropping systems (DMC)	DMC systems are described as being part of the family of practices known as CA. These systems have been developed to counteract soil degradation and to achieve more sustainable grain production. Under tropical and subtropical conditions the efficiency of such systems increases with the introduction of multifunctional cover crops growing in rotation with the main commercial crops or whenever climatic conditions are too risky for planting a commercial crop. The introduction of cover crops leads to a better utilization of available natural resources throughout the year, more biomass production, permanent soil protection and higher organic restitutions to the soil. DMC systems also offer environmental, economic and agronomic advantages to farmers.

[a]The sequence of terms in the table is in the order of decreasing severity, corresponding to increasing effectiveness of incorporating key elements of CA principles and practices, in line with CA definition and description, and with ranking of agriculture systems in Table 3 according to effectiveness of conservation of soils' capacities to yield plants and water on a sustainable basis.

disturbance means that roots of trees are not damaged by tillage, plus the system benefits from all the other advantages of CA including the enhancement of soil health and productivity. In fact, several tree crop systems in the developing and developed regions already practise some form of CA, but these systems can be further enhanced by improved crop associations including legumes, and integration with livestock. Alley cropping has been one innovation in this area that is beginning to offer productivity, economic and environmental benefits to producers who are able to take advantage of it (Friedrich *et al.*, 2009; Sims *et al.*, 2009).

Shifting agriculture, also referred to as bush fallow rotation or slash-and-burn or rotational farming, is based on the clearing of land to prepare a cultivation plot and subsequently abandoning this to regrowth and eventual natural reforestation. It is a stable form of agriculture under low population density regimes, but rising population density decreases regrowth time available for forests and leads to this system becoming unsustainable. Some shifting agriculture has evolved into sophisticated agroforestry management systems while in others it continues to be practised in response to poor land tenure policies. Shifting cultivation can be adapted to CA, changing from slash and burn systems to *slash and mulch* systems. This way, it is possible for the communities involved to harness a greater range of ecosystem services for themselves and for the greater society.

Benefits of Conservation Agriculture

CA represents a fundamental change to agricultural production systems. The main benefits are described in the following sections and provide an indication why farmers are adopting CA and why it deserves greater attention from the research and development community. However, the many synergistic interactions between components of CA practices are not yet fully understood. In general, scientific research on CA systems lags behind what farmers are discovering and adapting on their own initiative. This is partly because CA is a complex, knowledge-intensive set of systems which does not lend itself to easy scrutiny by a research community often driven by short-term reductionist thinking and approaches (Stoop & Kassam, 2005; Uphoff *et al.*, 2006; Kassam, 2008; Stoop *et al.*, 2009; Uphoff & Kassam, 2009).

Conservation Agriculture as a fundamental change in the agricultural production system

CA is a means of assuring production of plants and water recurrently and sustainably. It does this by favouring improvements in the condition of soils as rooting environments. CA is not a single technology, but a range based on one or more of the three main CA described above. CA functions best when all three key features are adequately

Table 3 A means of ranking agriculture systems according to the effectiveness of conservation of soils' capacities to yield plants and water on a sustainable basis

Generic agriculture system at mature functioning	***Key characteristics of CA ideal***	***Relative comparability with mature CA*** << ***furthest from*** ***closest to*** >>	***Notes***
Tillage without rotation	a. No soil stirring	■	
	b. Direct seeding	■	
	c. Permanent o.m. cover	■	
	d. Rotations + legumes	■ ►?	Only if pasture system with legumes
Tillage with rotation	a. No soil stirring	►?	Annuals may be in rotation with perennials
	b. Direct seeding	■	No, unless under-sowing pasture spp. into annual crops
	c. Permanent o.m. cover	►	If crops in rotation with pasture, for a proportion of the time the soil will be less exposed
	d. Rotations + legumes	◄ ►?	Crops themselves may include legumes in rotation; pastures may include clovers and/or other legumes
Conservation tillage/ Reduced tillage	a. No soil stirring	►	Cropping may be in rotation, with reduced severity of tillage
	b. Direct seeding	►	If system in transition to CA, seeding might be with 'minimum-disturbance' drills towards CA ideal
	c. Permanent o.m. cover	►	If crops in rotation with pasture, at least for a proportion of the time the soil will be less exposed
	d. Rotations + legumes	►	System may permit longer proportion of time/larger proportion of area actually with 100% cover

(*Continued*)

Table 3 *Continued*

Generic agriculture system at mature functioning	***Key characteristics of CA ideal***	***Relative comparability with mature CA << furthest from closest to>>***	***Notes***
Minimum tillage	a. No soil stirring	►	Specific aim of reduced soil disturbance, but frequency may not be reduced even if severity of disturbance is reduced
	b. Direct seeding	►	More likely to tend towards CA-type drill
	c. Permanent o.m. cover	►	Higher proportion of crop residues remain, and greater proportion of time/area likely to be covered
	d. Rotations + legumes	►?	Closer approximation to CA likely
Conservation agriculture	a. No soil stirring	■	Ideal CA, as yardstick
	b. Direct seeding	■	Ideal CA, as yardstick
	c. Permanent o.m. cover	■	Ideal CA, as yardstick
	d. Rotations + legumes	■	Ideal CA, as yardstick
Organic agriculture	a. No soil stirring	►?	Does not necessarily involve reduction in tillage
	b. Direct seeding	►?	‘Organic’ often in a tillage system, whose severity or frequency may/may not favour movement towards CA ideal
	c. Permanent o.m. cover	►?	‘Organic’ often in tillage system, whose severity may/may not favour movement towards CA ideal of 100% cover
	d. Rotations + legumes	►	‘Organic’ systems generally favour rotations and legumes in system
↓ Two other types of system may/can show certain positive attributes of CA ↓			

(*Continued*)

Table 3 *Continued*

Generic agriculture system at mature functioning	***Key characteristics of CA ideal***	***Relative comparability with mature CA <<furthest from closest to>>***	***Notes***
Shifting agriculture	a. No soil stirring	◄ ↔ ►	Sometimes severe, but ideally for one or few seasons only, within very long (decades-long) rotations with intervening 'tumble-down'/'bush fallow' years for soil recuperation. Annual crop yields low but overall sustainable in systems not pressured by population increase and without external inputs
	b. Direct seeding	► . . . .►	Possibly, of favoured spp. seeded through litter etc. of perennial 'bush' shrubs etc., at different stages of long rotation
	c. Permanent o.m. cover	► >>>>>>>>>>>>>>>> ► ←.	Increasing as 'bush-fallow' vegetation thickens. But, under pressure of rising rural population, time for recuperation under bush-fallow, before reopening for tillage, becomes shorter and less effective
	d. Rotations + legumes	► ►	Maybe of annuals in tillage years; regrowth 'bush' vegetation may include leguminous species in overall long-term 'bush rotation'
Agroforestry	a. No soil stirring	◄?►	Depends on proportions of area × frequency of planting of annual/biennial/perennial crops in chosen system, and on whether arrangement of preferred spp. on land surface is intermixed, vertically layered, alleys, etc.
	b. Direct seeding	►	Likely/often according to layout, timing, etc.
	c. Permanent o.m. cover	►	Likely for long periods and over a significant proportion of area
	d. Rotations + legumes	◄?►	Possible, in annual and/or perennial areas of layout

combined together in the field. It is significantly different from conventional tillage agriculture (Hobbs, 2007; Shaxson *et al.*, 2008). Ideally it avoids tillage once already damaged soil has been brought to good physical condition prior to initiating the CA system; maintains a mulch cover of organic matter on the soil surface at all times, for providing both protection to the surface and substrate for the organisms beneath; specifically uses sequences of different crops and cover-crops in multi-year rotations; and relies on nitrogen-fixing legumes to provide a significant proportion of N (Boddey *et al.*, 2006).

CA also relies on liberating other plant nutrients through biological transformations of organic matter. This can be augmented as necessary by suitable mineral fertilizers in cases of specific nutrient deficiencies, but organic matter also provides micronutrients that may not be available 'from the bag' (Flaig *et al.*, 1977). CA can retain and mimic the soil's original desirable characteristics ('forest floor conditions') on land being first opened for agricultural use. Throughout the transformation to agricultural production CA can sustain the health of long-opened land which is already in good condition, and it can regenerate that in poor condition (Doran & Zeiss, 2000). CA is a powerful tool for promoting soil and thus agricultural sustainability.

These multiple effects of CA when applied together are illustrated in Table 1 (Friedrich *et al.*, 2009). In contrast with tillage agriculture, CA can reverse the loss of organic matter, improve and maintain soil porosity and thus prolong the availability of plant-available soil water in times of drought (Derpsch *et al.*, 1991; Stewart, 2007; Mazvimavi & Twomlow, 2008). It can also reduce weed, insect pest and disease incidence by biological means, raise agro-ecological diversity, favour biological nitrogen fixation, and result in both raised and better stabilized yields accompanied by lowered costs of production (Blackshaw *et al.*, 2007; Mariki & Owenya, 2007; Gan *et al.*, 2008). Furthermore, CA can be explored for the purpose of achieving some of the objectives of the International Conventions on combating desertification, loss of biodiversity, and climate change (Benites *et al.*, 2002).

It is important to recognize that the improvements seen at macro-scale (e.g. yields, erosion avoidance, water supplies and farm profitability), are underlain and driven by essential features and processes happening at micro-scale in the soil itself. FAO (2008) indicates that:

> widespread adoption of CA has been demonstrated to be capable of producing large and demonstrable savings in machinery and energy use, and in carbon emissions, a rise in soil organic matter content and biotic activity, less erosion, increased crop-water availability and thus resilience to drought, improved recharge of aquifers and reduced impact of the apparently increased volatility in weather associated with climate change. It will cut production costs, lead to more reliable harvests and reduce risks especially for small landholders.

Higher stable yields and incomes from CA

As an effect of CA, the productive potential of soil rises because of improved interactions between the four factors of productivity: (a) physical: better characteristics of porosity for root growth, movement of water and root-respiration gases; (b) chemical: raised CEC gives better capture, release of inherent and applied nutrients: greater control/ release of nutrients; (c) biological: more organisms, organic matter and its transformation products; (d) hydrological: more water available.

The combination of the above features to raise productive potential makes the soil a better environment for the development and functioning of crop plants' roots. Improvements in the soil's porosity have two effects: a greater proportion of the incident rainfall enters into the soil; and the better distribution of pore-spaces of optimum sizes results in a greater proportion of the received water being held at plant-available tensions. Either or both together mean that, after the onset of a rainless period, the plants can continue growth towards harvest – for longer than would previously been the case – before the plant-available soil water is exhausted. In addition, increased quantities of soil organic matter result in improved availability, and duration of their release into the soil water, of needed plant nutrients – both those within the organic matter and those from off-farm. Thus the availability of both water and plant nutrients is extended together. Under these conditions, plants have a better environment in which to express their genetic potentials, whether they have been genetically engineered or not. Yield differences have been reported in the range of 20–120 per cent between CA systems and tillage systems in Latin America, Africa and Asia (Derpsch *et al.*, 1991; Pretty *et al.*, 2006; Landers, 2007; Ernstein *et al.*, 2008; FAO, 2008; Hengxin *et al.*, 2008; Rockstrom *et al.*, 2009). In Paraguay, small farmers have been able to successfully grow crops that initially were thought not to be appropriate for no-till systems, such as cassava. Planting cassava under CA in combination with cover crops has resulted in substantial yield increases, sometimes double the yields compared to conventional farming systems (Derpsch & Friedrich, 2009).

FAO (2001a) have indicated that:

> machinery and fuel costs are the most important cost item for larger producers and so the impact of CA on these expenditure items is critical. Most analyses suggest that CA reduces the machinery costs. Zero or minimum tillage means that farmers can use a smaller tractor and make fewer passes over the field. This also results in a lower fuel and repair costs. However, this simple view masks some complexities in making a fair comparison. For example, farmers may see CA as a complement to rather than as a full substitute for their existing practices. If they only partially switch to CA (some fields or in some years), then their machinery costs may rise as they must now provide for two cultivation systems, or they may simply use their existing machinery inefficiently in their CA fields.

No-till, or a reduced proportion of the area needing tillage (e.g. planting basins or *zai/tassa*), requires less input of energy per unit area, per unit output, and lower depreciation rates of equipment. Over time, less fertilizer is required for the same output (Lafond *et al.*, 2008). Production costs are thus lower, thereby increasing profit margins as well as lessening emissions from tractor fuel (Hengxin *et al.*, 2008). Better soil protection by mulch cover minimizes both runoff volumes and the scouring of topsoil, carrying with it seeds and fertilizers. Such losses represent unnecessary cost, wasted rainwater and wasted energy. Their avoidance increases the margin between profits and costs, which formerly, under tillage agriculture, were accepted as 'normal' expenses to be anticipated.

CA systems are less vulnerable to insect pests, diseases and drought effects because better soil and plant conditions include also greater biotic diversity of potential predators on pests and diseases, while crop rotations break insect pest build-ups. Here, much of the cost of avoiding or controlling significant pest attacks is diminished because of it being undertaken by healthier plants, breaks in pest life cycles and natural predators (Settle & Whitten, 2000; Evers & Agostini, 2001; Blank, 2008). Research conducted by Kliewer *et al.*, (1998) in Paraguay and Sorrensen and Montoya (1984) in Brazil has shown that crop rotation and short-term green manure cover crops can reduce the cost of herbicides drastically, due to reduction in weed infestation over time (Blackshaw *et al.*, 2007). While many still think that green manure cover crops are economically not viable, farmers in Brazil and Paraguay have learned that the economics of CA can be substantially increased with their use (Derpsch *et al.*, 1991; Derpsch, 2008a).

As a result, the financial benefits for farmers in Latin America who have adopted CA have been striking (Landers, 2007). However, these take time to fully materialize. Sorrenson (1997) compared the financial profitability of CA on 18 medium- and large-sized farms with conventional practice in two regions of Paraguay over 10 years. By year 10, net farm income had risen on CA farms from USD10,000 to over USD30,000, while on conventional farms net farm income fell. Medium- and large-scale CA farmers had experienced:

- Less soil erosion, improvements in soil structure and an increase in organic matter content, crop yields and cropping intensities.
- Reduced time between harvesting and sowing crops, allowing more crops to be grown over a 12-month period.
- Decreased tractor hours, farm labour, machinery costs, fertilizer, insecticide, fungicide and herbicide, and cost savings from reduced contour terracing and replanting of crops following heavy rains.
- Lower risks on a whole-farm basis of higher and more stable yields and diversification into cash crop (FAO, 2001b).

Such effects are cumulative over space, and can accumulate over time from degraded condition to improved stabilized condition, with yields and income rising over time, as in this example of large-scale wheat production under CA in Kazakhstan. Figure 1 shows the development of wheat yields and financial benefits after changing from conventional tillage to no-till agriculture on mechanized farms in northern Kazakhstan. The internal rate of return to investment (IRR) is 28 per cent (Fileccia, 2008). Thus, farmers should turn away from the struggle to reach the highest yield. Instead they should aim for the best economic yield. Figure 1 indicates that CA can achieve this goal even under the relatively marginal conditions prevailing in northern Kazakhstan.

Further, in Paraguay, yields under conventional tillage declined 5–15 per cent over a period of 10 years, while yields from zero-till CA systems increased 5–15 per cent. Over the same period, fertilizer and herbicide inputs dropped by an average of 30–50 per cent in the CA systems (Derpsch, 2008a). In Brazil, over a 17-year period, maize and soybean yields increased by 86 and 56 per cent respectively, while fertilizer inputs for these crops fell by 30 and 50 per cent respectively. In addition, soil erosion in Brazil decreased from 3.4–8.0 t/ha under conventional tillage to 0.4 t/ha under no-till, and water loss fell from approximately 990 to 170 t/ha (Derpsch, 2008a).

Climate change adaptation and reduced vulnerability

Reduced vulnerability to effects of drought, less erosion, and lesser extremes of soil temperatures represent a managed adaptation of CA systems to climate change effects such as, for example, more intense rainstorms, increased daily ranges of temperatures, and more severe periods of drought. Overall, CA systems have a higher adaptability to climate change because of the higher effective rainfall due to higher infiltration and therefore minimum flooding and soil erosion as well as greater soil moisture-holding capacity.

The advantage of CA over tillage agriculture in terms of the greater soil moisture-holding capacity and therefore duration of plant-available soil moisture is illustrated by Derpsch *et al.* (1991), who show that soil moisture conditions in rooting zones through growing seasons under CA are better than under both minimum and conventional tillage. Thus crops under CA systems can continue towards maturity for longer than those under conventional tillage. In addition, the period in which available nutrients can be taken up by plants is extended, increasing the efficiency of use. The greater volume and longer duration of soil moisture's availability to plants (between the soil's field capacity and wilting point) has significant positive outcomes both for farming stability and profitability. The range of pore sizes which achieves this

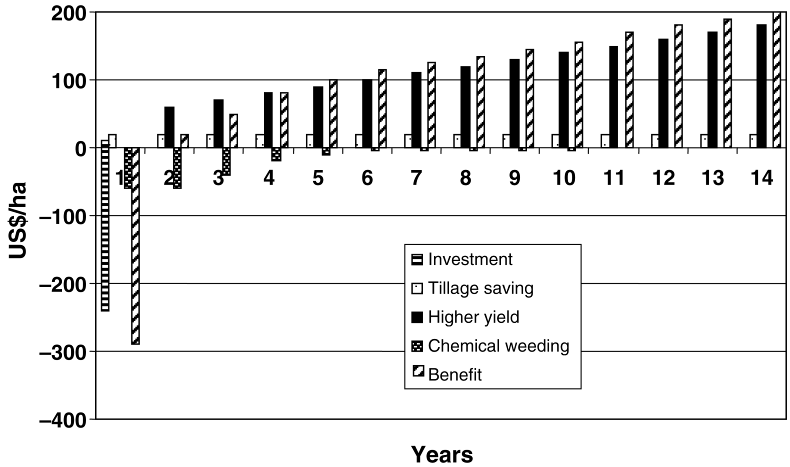

Figure 1 Financial benefits of Conservation Agriculture in wheat production in Northern Kazakhstan (IRR=28 per cent)

also implies the presence of larger pores which contribute to through-flow of incident rainwater down to the groundwater (Shaxson *et al.*, 2008).

Infiltration rates under well managed CA are much higher over extended periods due to better soil porosity. In Brazil (Landers, 2007), a 6-fold difference was measured between infiltration rates under CA (120 mm per hour) and traditional tillage (20 mm per hour). CA thus provides a means to maximize effective rainfall and recharge groundwater as well as reduce risks of flooding. Due to improved growing season moisture regime and soil storage of water and nutrients, crops under CA require less fertilizer and pesticides to feed and protect the crop, thus leading to a lowering of potential contamination of soil, water, food and feed. In addition, in soils of good porosity, anoxic zones hardly have time to form in the root zone, thus avoiding problems of the reduction of nitrate to nitrite ions in the soil solution (Flaig *et al.*, 1977).

Good mulch cover provides 'buffering' of temperatures at the soil surface which otherwise are capable of harming plant tissue at the soil/atmosphere interface, thus minimizing a potential cause of limitation of yields. By protecting the soil surface from direct impact by high-energy raindrops, it prevents surface-sealing and thus maintains the soil's infiltration capacity, while at the same time minimizing soil evaporation.

In the continental regions of Europe, Russia and North America, where much annual precipitation is in the form of snow in the winter, CA provides a way of trapping snow evenly on the field which may otherwise blow away, and also permits snow to melt evenly into the soil. In the semi-arid areas of continental Eurasia, one-third or more of the precipitation is not effectively used in tillage systems, forcing farmers to leave land fallow to 'conserve' soil moisture, leading to extensive wind erosion of topsoil from fallow land, and to dust emissions and transport over large distances (Brimili, 2008). Under CA, more soil moisture can be conserved than when leaving the land fallow, thus allowing for the introduction of additional crops including legume cover crops into the system (Blackshaw *et al.*, 2007; Gan *et al.*, 2008). In the tropics and subtropics, similar evidence of adaptability to rainfall variability has been reported (Ernstein *et al.*, 2008; Rockstrom et al., 2009).

Reduced greenhouse gas emissions

No-till farming also reduces the unnecessarily rapid oxidation of soil organic matter to CO_2 which is induced by tillage (Reicosky, 2008; Nelson *et al.*, 2009). Together with the addition of mulch as a result of saving crop residues in situ as well as through root exudation of carbon compounds directly into the soil during crop growth (Jones, 2007), there is a reversal from net loss to net gain of carbon in the soil, and the commencement of long-term processes of carbon sequestration (West & Post, 2002; Blanco-Canqui & Lal, 2008; CTIC/FAO, 2008).

Making use of crop residues and the direct rhizospheric exudation of carbon into the soil represents the retention of much of the atmospheric C captured by the plants and retained above the ground. Some becomes transformed to soil organic matter of which part is resistant to quick breakdown (though still with useful attributes in soil), and represents net C-accumulation in soil, eventually leading to C-sequestration. Tillage, however, results in rapid oxidation to CO_2 and loss to the atmosphere. Expanded across a wide area, CA has the potential to slow/reverse the rate of emissions of CO_2 and other greenhouse gases by agriculture.

Studies in southern Brazil show an increase in carbon in the soil under CA. According to Testa *et al.* (1992), soil carbon content increased by 47 per cent in the maize–lablab system, and by 116 per cent in the maize–castor bean system, compared to the fallow–maize cropping system which was taken as a reference. Although exceptions have been reported, generally there is an increase in soil carbon content under CA systems, as shown by the analysis of global coverage by West and Post (2002). In systems where nitrogen was applied as a fertilizer, the carbon contents increased even more. Baker *et al.* (2007) found that crop rotation systems in CA accumulated about 11 t/ha of carbon after 9 years. Under tillage agriculture and with monoculture systems the carbon liberation into the atmosphere was about 1.8 t/ha per year of CO_2 (FAO, 2001b).

With CA, reduced use of tractors and other powered farm equipment results in lower emissions. Up to 70 per cent in fuel savings have been reported (FAO, 2008). CA systems can also help reduce the emissions for other relevant greenhouse gases, such as methane and nitrous oxides, if combined with other complementary techniques. Both methane and nitrous oxide emissions result from poorly aerated soils, for example from permanently flooded rice paddies, from severely compacted soils, or from heavy poorly drained soils. CA improves the internal drainage of soils and the aeration and avoids anaerobic areas in the soil profile, so long as soil compactions through heavy machinery traffic are avoided and the irrigation water management is adequate.

The soil is a dominant source of atmospheric N_2O (Houghton *et al.*, 1997). In most agricultural soils biogenic formation of nitrous oxide is enhanced by an increase in available mineral N which, in turn, increases the rates of aerobic microbial nitrification of ammonia into nitrates and anaerobic microbial reduction (denitrification) of nitrate to gaseous forms of nitrogen (Bouwman, 1990; Granli & Bøckman, 1994). The rate of production and emission of N_2O depends primarily on the availability of a mineral N source, the substrate for nitrification or denitrification, on soil temperature, soil water content, and (when denitrification is the main process) the availability of labile organic compounds. These variables are universal and apply to cool temperate and also warm tropical ecosystems. Addition of fertilizer N, therefore, directly results in extra N_2O formation as an intermediate in the reaction sequence of both processes which leaks from microbial cells into the atmosphere (Firestone & Davidson, 1989). In addition, mineral N inputs may lead to indirect formation of N_2O after N leaching or runoff, or following gaseous losses and consecutive deposition of N_2O and ammonia. CA generally reduces the need for mineral N by 30–50 per cent, and enhances nitrogen factor productivity. Also, nitrogen leaching and nitrogen runoff are minimal under CA systems. Thus overall, CA has the potential to lower N_2O emissions (e.g., Parkin & Kaspar, 2006), and mitigate other GHG emissions as reported by Robertson *et al.* (2000) for the mid-west USA and Metay *et al.* (2007) for the Cerrado in Brazil. However, the potential for such results applying generally to the moist and cool UK conditions has been challenged, for example, by Bhogal *et al.* (2007) and questions have been raised over their validity due to the depth of soil sampled, particularly for N_2O emissions and the overall balance of GHG emissions (expressed on a carbon dioxide (CO_2-C) equivalent basis).

Better ecosystem functioning and services

Societies everywhere benefit from the many resources and processes supplied by nature. Collectively these are known as ecosystem services (MEA, 2005), and include clean drinking water, edible and non-edible biological products, and processes that decompose and transform organic matter. Five categories of services are recognized: provisioning services such as the production of food, water, carbon and raw materials; regulating, such as the control of climate, soil erosion and pests and disease; supporting, such as nutrient and hydrological cycles, soil formation and crop pollination; cultural, such as spiritual and recreational benefits; and preserving, which includes guarding against uncertainty through the maintenance of biodiversity and sanctuaries.

CA's benefits to ecosystem services, particularly those related to provisioning, regulating and supporting, derive from improved soil conditions in the soil volume used by plant roots. The improvement in the porosity of the soil is effected by the actions of the soil biota which are present in greater abundance in the soil under CA. The mulch on the surface protects against the compacting and erosive effects of heavy rain, damps down temperature fluctuations, and provides energy and nutrients to the organisms below the soil surface. When the effects are reproduced across farms in a contiguous micro-catchment within a landscape, the ecosystem services provided – such as clean water, sequestration of carbon, avoidance of erosion and runoff – become more apparent. The benefits of more water infiltrating into the ground beyond the depth of plant roots is perceptible in terms of more regular streamflow from groundwater through the year, and/or more reliable yields of water from wells and boreholes (e.g., Evers & Agostini, 2001). The benefits of carbon capture become apparent in terms of the darkening colour and more crumbly 'feel' of the soil, accompanied by improvements in crop growth, plus less erosion and hence less deposition of sediment downstream in streambeds.

Legumes in CA rotations provide increased in situ availability of nitrogen, thus diminishing the need for large amounts of applied nitrogenous fertilizers

(Boddey *et al.*, 2006). Also, there is increasing evidence of a significant amount of 'liquid carbon' being deposited into the soil through root exudation into the rhizosphere (Jones, 2007).

Society gains from CA on both large and small farms by diminished erosion and runoff, less downstream sedimentation and flood damage to infrastructure, better recharge of groundwater, more regular streamflow throughout the year with the less frequent drying up of wells and boreholes, cleaner civic water supplies with reduced costs of treatment for urban/domestic use, increased stability of food supplies due to greater resilience of crops in the face of climatic drought, and better nutrition and health of rural populations, with less call on curative health services (ICEPA/SC, 1999; World Bank, 2000; Pieri *et al.*, 2002).

In CA systems, the sequences and rotations of crops encourage agrobiodiversity as each crop will attract different overlapping spectra of microorganisms. The optimization of populations, range of species and effects of the soil-inhabiting biota is encouraged by the recycling of crop residues and other organic matter which provides the substrate for their metabolism. Rotations of crops inhibit the build-up of weeds, insect pests and pathogens by interrupting their life cycles, making them more vulnerable to natural predator species, and contributing development-inhibiting allelochemicals. The same crop mixtures, sequences and rotations provide above-ground mixed habitats for insects, mammals and birds.

The adoption of Conservation Agriculture

Global area and regional distribution

Although much of the CA development to date has been associated with rain-fed arable crops, farmers can apply the same principles to increase the sustainability of irrigated systems, including those in semi-arid areas. CA systems can also be tailored for orchard and vine crops with the direct sowing of field crops, cover crops and pastures beneath or between rows, giving permanent cover and improved soil aeration and biodiversity. The common constraint, according to farmers, to practising this latter type of intercropping is competition for soil water between trees and crops. However, careful selection of deep-rooting tree species and shallow-rooting annuals resolves this. Functional CA systems do not replace but should be integrated with current good land husbandry practices (Shaxson, 2006).

Because of the benefits that CA systems generate in terms of yield, sustainability of land use, incomes, timeliness of cropping practices, ease of farming and ecosystem services, the area under CA systems has been growing rapidly, largely as a result of the initiative of farmers and their organizations (Figure 2). It is estimated that, worldwide, there are now some 106 million ha of arable crops grown each year without tillage in CA systems. Table 4 provides information on country-specific arable and permanent cropland area under CA, and as percentage of total arable and permanent cropland area.

A useful overview of the adoption of CA in individual countries is given by Derpsch and Friedrich (2009). Except in a few countries (USA, Canada, Australia, Brazil, Argentina, Paraguay, Uruguay, Kazakhstan, China, Kenya, Tanzania, Lesotho, Malawi, South Africa), these approaches to sustainable farming have not been 'mainstreamed' in agricultural development programmes or backed by suitable policies and institutional support. Consequently, the total area under CA is still small (about 7 per cent) relative to areas farmed using tillage. Nonetheless, the rate of increase globally since 1990 has been at the rate of some 5.3 million ha per annum, mainly in North and South America and in Australia and New Zealand.

Currently, South America has the largest area under CA with 49,586,900 ha (46.6 per cent of total global area under CA) followed by North America (39,981,000 ha, 37.5 per cent). Australia and New Zealand have 12,162,000 ha (11.4 per cent), Asia 2,630,000 ha (2.3 per cent), Europe 1,536,100 ha (1.4 per cent) and Africa 470,100 ha (0.4 per cent).

Area of CA in industrialized countries

No-till agriculture in the modern sense originated in the USA in the 1950s, and from then until 2007 the USA had the largest area under no-till worldwide. In the USA, no-till currently accounts for some 25.5 per cent of all cropland. Conventional agriculture

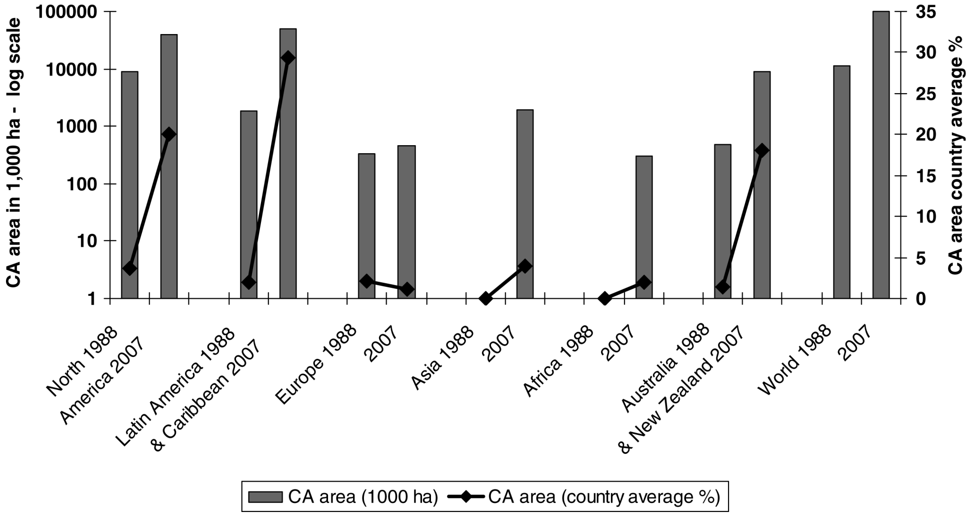

Figure 2 Development of Conservation Agriculture over the last 20 years by world region in total area (ha) and as average percentage across the adopting countries of the respective region (from FAO, 2008)

with tillage remains in the majority even if CA is a valid option for farmers, as compared with southern Latin America where no-till has become the majority agricultural system with 60 per cent of the cropland area. According to CTIC (2005), only half of the total area under no-till in the USA is being permanently not tilled, some 26.5 million ha, corresponding to 15.3 per cent of total arable and permanent cropland. This occasional tillage prevents the system from reaching its optimum balance, as the soil is disturbed from time to time. Research has shown that it takes more than 20 years of continuous no-till to reap the full benefits of CA. Farmers who practise rotational tillage (plough or till their soils occasionally) will not experience the full benefits of the system (Derpsch, 2005).

In Canada, CA is now practised on some 13.5 million ha (25.9 per cent of arable and permanent crop area), although the no-till technology is used over a much larger area, 46.1 per cent of cropland (Derpsch & Friedrich, 2009). In Australia, CA has been widely embraced by farmers (12 million ha). It has improved weed control, time of sowing, given drought tolerance and has enabled dry regions to use water most efficiently (Crabtree, 2004; Flower *et al.*, 2008). But inappropriate seeding machines which move the mulch too much, and sheep that graze crop residues are leading to an insufficient soil cover. New Zealand has about 160,000 ha under CA, which corresponds to 17 per cent of all cropland area. New Zealand farmers were among the first to use and develop the no-till technology: in the 1970s, pasture renovation without tillage was tried and practised successfully. Later, annual crops were seeded with the no-till. However, the majority of the increase in CA area has occurred since 2000.

CA is not widespread in Europe (Basch *et al.*, 2008; Lahmar, 2009): no-till systems do not exceed 2 per cent of the agricultural cropland. Since 1999 ECAF (European Conservation Agriculture Federation) has been promoting CA in Europe, and adoption is visible in Spain, France, Germany, Ukraine and Finland, with some farmers at 'proof of concept' stage in the UK, Ireland, Portugal, Switzerland and Italy.

Area of CA in developing countries

Brazil has the longest experience in CA, and now has 25.5 million ha under various forms of CA. Since its first appearance in 1972, many useful lessons have originated from Brazil and from neighbouring Argentina and Paraguay, which now have respectively 19.7 and 2.4 million ha of CA. They have also set important precedents for the engagement of farmers as principal actors in the development and adaptation of new technologies.

Table 4 Conservation Agriculture adoption by country over the past 30 years (in 1000 ha) and in percentage of total arable and permanent cropland area for 2008–2009

Country	***1973–1977***	***1978–1982***	***1983–1987***	***1988–1992***	***1993–1997***	***1998–2002***	***2003–2007***	***2008–2009***	***CA % of 2008–2009 crop area***
Argentina		2	6	500	3,950	15,001	19,719	19,719	58.8
Australia	100	100	400	400			9,000	12,000	26.9
Bolivia						240	706	706	18.4
Brazil	57	232	650	1,350	8,847	18,744	25,502	25,502	38.3
Canada				1,951	4,592	8,823	13,481	13,481	25.9
Chile							120	180	10.3
China							100	1,330	0.9
Colombia							102	102	2.9
Finland								200	8.8
France	50	50	50	50			150	200	10.2
Germany							354	354	2.9
Hungary							8	8	0.2
Ireland							0.1	0.1	<0.1
Italy							80	80	0.8
Kazakhstan							600	1,300	5.7
Kenya							15	33.1	0.6
Lesotho							0.13	0.13	<0.1
Mexico							22.8	22.8	0.1
Morocco								4	<0.1
Mozambique							9	9	0.2
Netherlands	2	2	5						
New Zealand	75	75	75	75	63.2	63.2	162	162	17.4
Paraguay					200	1,200	2,094	2,400	54.5
Portugal							25	25	1.5
Slovakia							10	10	0.7

(*Continued*)

Table 4 *Continued*

Country	*1973–1977*	*1978–1982*	*1983–1987*	*1988–1992*	*1993–1997*	*1998–2002*	*2003–2007*	*2008–2009*	*CA % of 2008–2009 crop area*
South Africa	1	1					300	368	2.4
Spain							300	650	3.7
Sudan								10	<0.1
Switzerland							9	9	2.1
Tunisia						0.03	6	6	0.1
Ukraine								100	0.3
UK	200		275	275			24	24	0.4
USA	2,200	2,200	4,800	6,839	17,361	22,400	26,500	26,500	15.3
Uruguay						338	554	655.1	47.4
Venezuela							300	300	9.0
Zambia						40		40	0.8
Zimbabwe								15	0.4
TOTAL	2,685	2,661	6,261	11,440	35,013	66,849.03	100,253.03	106,505.23	6.9

Source: FAO AQUASTAT, 2009; http://www.fao.org/ag/ca; FAO STAT, 2009.

Brazil took the initiative when herbicides (paraquat and diquat) and direct-drilling equipment became available in the USA, and it became clear that conventional ploughing was leading to a severe environmental and economic crisis for farmers in southern Brazil. Progressive and wealthy farmers led the way, some travelling to the USA to learn about their soil conservation and management systems and to purchase direct-drilling equipment. Common interest groups were then formed among large-scale farmers and then by small-scale farmers. CA has emerged mainly as a result of farmer innovation together with problem-solving support from input supply companies, state and federal research and extension organizations, universities, as well as long-term funding commitments from international donors such as the World Bank and GTZ. However, the momentum for innovation and adoption still is with farmers and their organizations.

Apart from enabling their land to be cropped more intensively without risk of degradation, CA attracted Brazilian farmers because it increased crop yields (at least 10–25 per cent), greatly reduced surface runoff and soil erosion, and cut tractor use, resulting in big savings in fuel and production costs. Such benefits explain why today, Latin American farmers practise zero-tillage CA on a continuous basis on some 50 million ha.

Paraguay has experienced a continuous and steady growth of CA adoption, almost all of it over the past 10 years. Tillage practices have disappeared almost completely. In tractor mechanized farming systems, about 90 per cent (2.4 million ha in 2008) of all crop area is under CA (Derpsch & Friedrich, 2009). Similarly, in small farmer production systems with animal traction or manual systems, no-till practices have increased to about 30,000 ha covering 22,000 small farmers. The increased interest in small farmer CA systems has been a result of government support that provides grants for buying no-till equipment.

In Bolivia CA practices increased in the last 10 years, especially in the lowlands in the east of the country where the main crop is soybeans whose area has increased from around 240,000 ha in the year 2000 to 706,000 ha in the year 2007 (Derpsch & Freidrich, 2009). The occurrence of wind erosion in conventional tillage systems has been one of the major driving forces for adoption. Also the increased water use efficiency under no-till system is valued by farmers in a region with low and erratic rainfall.

Uruguay has also seen a significant increase in permanent no-till practices, with some 47 per cent of its arable and permanent cropland switching to CA systems in the last 10 years. Some 65 per cent of arable crops are seeded on rented land for which contracts are renewed every year, and this hinders the planning of medium-term crop rotation and investment strategies. In Uruguay the integration of crops with livestock is very popular and CA systems fit well into the requirements for crop–livestock production systems. Pastures are grown for several years until they show signs of degradation. Crops are then grown for several years according to the needs of the farmers and the market situation. Venezuela, Chile, Colombia and Mexico have modest amounts of their land under no-till systems, ranging from some 23,000 ha in Mexico to 300,000 ha in Venezuela (Derpsch & Friedrich, 2009).

The main crops grown under CA in Latin America include soybean, maize, wheat, sunflower, canola as well as cassava, potato and a number of horticultural and cover crops. CA practices are also being applied to perennial crops and to tree crops. Soil cover is achieved by growing cash crops and cover crops either in association or sequentially. Main cover crops include oats, oilseed-radish, rye, lupin, vetch, *Mucuna* (velvet bean), *Dolichos* and *Cajanus* (pigeon pea). In some cases, especially among small-scale farmers, herbicide use can be reduced by direct-drilling the seed into a cover crop that has been flattened using a knife roller. Specialized no-till equipment has been developed in Brazil and the Americas, including tractor-mounted, animal drawn and hand tools (including jab planters). These are being exported to Africa and Asia and being adapted there for local use and manufacture.

Asian and African countries have seen uptake of CA in the past 10–15 years. In Central Asia, a fast development of CA can be observed in the last 5 years in Kazakhstan and the neighbouring Russian areas. Kazakhstan now has 3.5 million ha under reduced tillage, mostly in the northern drier provinces, and of this 1.3 million ha (5.7 per cent of crop area) are 'real' CA with permanent no-till and rotation. This puts Kazakhstan among the top ten countries with the largest cropland area under CA systems. CA has had a rapid development in recent years as a result of farmers' interest, accumulated research knowledge, facilitating government policies and an active input supply sector (Derpsch & Friedrich, 2009). China too has equally a dynamic development of CA. It began 10 years ago with research, then the adoption increased during the last few years and the technology has been extended to the rice production system. Now more than 1.3 million ha are under CA in China and 3,000 ha in DPR Korea where the introduction of CA has made it possible to grow two successive crops (rice, maize or soya as summer crop, winter wheat or spring barley as winter crop) within the same year, through direct drilling of the second crop into the stubble of the first. The feasibility of growing potatoes under zero tillage has also been demonstrated in DPR Korea (FAO, 2007).

In the Indo-Gangetic plains across India, Pakistan, Nepal and Bangladesh, in the wheat–rice cropping system, there is large adoption of no-till wheat with some 5 million ha, but only marginal adoption of permanent no-till systems and full CA (Hobbs *et al.*, 2008). This is because virtually all rice is grown under some form of tillage system. In India, the adoption of no-till practices by farmers has occurred mainly in the wheat–rice double cropping system and has been adopted primarily for the wheat crop. The main reason for this has been that tillage takes too much time resulting in delayed seeding and yield loss of the wheat crop after rice (Hobbs & Gupta, 2003; Hobbs *et al.*, 2008). The Rice–Wheat Consortium for the Indo-Gangetic Plains, an initiative of CGIAR, led by IRRI and CIMMYT and involving several National Agricultural Research Centres, has been promoting no-till practice and it is mainly their efforts that have resulted in the massive uptake of no-till wheat in the region (Ernstein *et al.*, 2008). The uptake of the technology was rapid in the northwestern states which are relatively better endowed with respect to irrigation, mechanization and where the size of holdings is relatively large (3–4 ha) compared to the eastern region which is less equipped and mechanized and where the average land holding is small (1 ha) (Derpsch & Friedrich, 2009).

Among the most encouraging research experiences has been the CA work developed in the dry Mediterranean environments of North Africa in Morocco (Mrabet, 2007, 2008) and Tunisia (Ben-Hammouda *et al.*, 2007) where highly innovative adaptations have been made to the low and unpredictable rainfall. In sub-Saharan Africa, innovative participatory approaches are being used to develop supply chains for producing CA equipment targeted at smallholders. Similarly, participatory learning approaches such as those based on the principles of farmer field schools (FFS) are being encouraged to strengthen farmers' understanding of the principles underlying CA and how these can be adapted to local situations. The corresponding programmes recognize the need to adapt systems to the very varied agro-ecosystems of the regions, to the extreme shortage of land faced by many farmers and to the competing demands for crop residues for livestock and fuel – problems that are particularly pronounced amongst small-scale farmers in Africa in the semi-arid tropical and Mediterranean regions.

CA is now beginning to spread to the sub-Saharan Africa region, particularly in eastern and southern Africa, where it is being promoted by FAO, CIRAD, the African Conservation Tillage Network, ICRAF, CIMMYT, ICRISAT, IITA (Haggblade & Tembo, 2003; Baudron *et al.*, 2007; Boshen *et al.*, 2007; Kaumbutho & Kienzle, 2007; Nyende *et al.*, 2007; SARD, 2007; Shetto & Owenya, 2007; Ernstein *et al.*, 2008). Building on indigenous and scientific knowledge and equipment design from Latin America, farmers in at least 14 African countries are now using CA (in Kenya, Uganda, Tanzania, Sudan, Swaziland, Lesotho, Malawi, Madagascar, Mozambique, South Africa, Zambia, Zimbabwe, Ghana and Burkina Faso). CA has also been incorporated into the regional agricultural policies by NEPAD (New Partnership for Africa's Development) and more recently by AGRA (Alliance for a Green Revolution in Africa). In the specific context of Africa (where the majority of farmers are resource-poor and rely on less than 1 ha), CA systems are relevant for addressing the old as well as new challenges of climate change, high energy costs, environmental degradation and labour shortages. In Africa CA is expected to increase food production while reducing negative effects on the environment and energy costs, and result in the development of locally adapted technologies consistent with CA principles (FAO, 2008).

While large numbers of small-scale farmers (in Paraguay, China and various African countries) have adopted CA practices, experience indicates that the spread tends to be at a slower pace than among larger-scale farmers. With food security among their major objectives, many small-scale farmers are hesitant to invest scarce labour, land, seed and fertilizer in cover crops that do not result in something to eat or to sell. They also suffer from restricted access to relevant knowledge as well as to inputs or credit. As a result, there is an increasing recognition of the need to encourage farmers to move towards full adoption of CA at their own pace, testing out promising approaches initially on small areas of their farms and progressively expanding as their confidence in the results develops. However, because of these constraints, some researchers (e.g., Gowing & Palmer 2008; Giller *et al.*, 2009) have suggested that either the evidence for the case for CA is not adequate or that under present circumstances CA is inappropriate for the majority of resource-constrained smallholder farmers and farming systems in Africa (Giller *et al.*, 2009). The global evidence of CA adoption presented in this paper and elsewhere (Fowler & Rockstrom, 2001; Haggblade & Tembo, 2003; FAO, 2008) suggests that elements can work for small farmers.

Global distribution of CA across climate zones

CA is practised in all climate zones of the world where annual and perennial crops can be grown, from the tropics and subtropics to the temperate regions (FAO, 2008). Functional examples exist in the tropics and subtropics (summer rainfall), in the moist (subhumid) and dry savannah and the humid forest environments in Latin America (e.g., Brazil, Colombia, Venezuela, Argentina, Bolivia, Chile, Mexico, Paraguay, Uruguay), sub-Saharan Africa (e.g., Kenya, Tanzania, Zimbabwe, Zambia, Swaziland, South Africa, Madagascar, Ghana), Asia (e.g., India, Pakistan, China), northern Australia and the USA. In the African tropical Sahel zone, CA is practised in the form of *zai* pits, which involve concentrating available nutrients and moisture supply around and close to the plants or trees.

In the subtropics, CA is practised in the winter rainfall areas with Mediterranean-type environments in Latin America (e.g., Chile, Argentina), in North Africa (Tunisia, Morocco), West and Central Asia (Syria, Kazakhstan), and in California, USA. In the temperate regions, CA is practised in Latin America (e.g., Chile, Argentina), Asia (e.g., DPR Korea, China), North America (USA, Canada) and Europe (e.g., Spain, France, Germany, Ukraine and Finland).

Distribution of CA across farm types

CA should be applicable to any size of farm (large land holdings, commercial farmers, medium-scale farmers, small-scale farmers). In Latin America, Africa and Asia, it has been shown to work in large, medium and small farms. However, the area of CA to date comprises mainly large farms which, under labour shortage situations, can capture the economies of scale with the use of CA machinery and equipment.

In 2002, it was estimated that of the total area under CA, only a small proportion (about 450,000 ha) was practised on small farms by about 200,000 farmers. This is because only few countries (e.g., Brazil) have seriously invested in research and developed technologies to suit small farmers. Brazil is also among the few countries that manufacture equipment for small farmers (e.g., one- or two-row seeding machines, sprayers, knife rollers, fertilizer and lime spreaders for animal traction, or hand jab planters). However, in 2005, according to FEBRAPDP (Federation of No-Till Farmers of Brazil), there were 500,000–600,000 ha of no-till being adopted by small farmers with animal traction. This corresponds to some 100,000 small farmers using no-till practice in Brazil. In Paraguay the number of small farmers adopting CA practices has also grown rapidly recently. In 2005, it was estimated that 12,000 farmers were using no-till on about 30,000 ha. Another region with a large number of small farmers adopting no-till technology is the Indo-Gangetic Plains. Here some 700,000 small farmers are estimated to be using the technology on some 2 million ha (Hobbs *et al.*, 2000, Hobbs, 2007). To date, the area under CA in sub-Saharan Africa is small, about 470,100 ha, of which 368,000 ha are in South Africa. Most of the promotion is among small farmers, and there is a steadily growing movement in the region outside South Africa involving already far more than 100,000 small-scale farmers (Derpsch & Friedrich, 2009).

Based on the experience of CA adoption as a knowledge-intensive set of principles and practices, it may be assumed that the CA adoption rate will grow at a slower pace in smallholder farming systems than in mechanized medium- and large-scale systems (FAO, 2008). The most important reason is that too little research and development attention is being paid to the special needs of smallholders, especially on affordable CA equipment. Another important reason is the logistics of how to reach a greater number of small farmers in remote areas, with shrinking budgets for extension services. While mass media strategies can work well with well-educated medium- and large-scale farmers, individual assistance over a period of time is generally necessary when working with small-scale subsistence farmers. Lately, extension initiatives involving experiential testing and learning based on FFS-type approaches, including the use of on-farm farmer discovery benchmark sites, are showing promising results, particularly in Africa (Baudron *et al.*, 2007; Kaumbutho & Kienzle, 2007; Shetto & Owenya, 2007; FAO, 2009; Rockstrom *et al.*, 2009; Silici, 2009).

Concluding comments

Ecosystems are subdivisions of the biosphere, and by definition have living components. Their sustainable functioning is dependent on their self-repeating and self-repairing dynamics in balance with the attributes of the systems' non-living components and forces (Dasmann, 1984). The concatenation (linking-together) of increasing problems provoked by (a) adverse climate change, (b) growth of human populations and associated demands for services provided by ecosystems, and (c) ongoing net degradation of many lands' productive capacities, threatens the integrity, resilience, self-recuperating capacity and sustainable functioning of the ecosystems which benefit human life both directly and indirectly.

A key feature of CA is the encouragement of the soil-improving recycling of carbon from atmosphere to plants to soil-inhabiting organisms and to soil organic matter (as both a reservoir for carbon and a substrate for soil biota) and finally to the atmosphere. CA maintains and can raise levels of soil organic matter beneficial to biotic functioning, and minimizes excessive rates of its oxidation back to carbon dioxide. By this means both resilience of agricultural ecosystems systems and their soils' capacity for self-repair of their architecture in the face of adverse conditions of climate and/or of poor management are strengthened.

With increasing awareness of the need for sustainable production intensification, and of improved understanding of how to achieve it, CA is an option for sustainable and productive agriculture. CA is sometimes referred to as win–win agricultural production systems as it is applied globally on over 105 million ha of cropland across different agro-ecosystems and cropping systems. In the 1940s Edward Faulkner in his revolutionary 'Ploughman's Folly' stated that 'no one has ever advanced a scientific reason for ploughing'. Wherever CA has been adopted and practised properly it has proven beneficial.

Yet the question arises: if CA is so good, why is it not spreading faster? CA is knowledge-intensive and a complex system to learn and implement. It cannot be reduced to a simple standard technology and thus pioneers and early adopters face many hurdles before the full benefits of CA can be reaped (Derpsch, 2008b). Indeed, the scaling up of CA practices to achieve national impact requires a dynamic complement of enabling policies and institutional support to producers and supply chain service providers (Pieri *et al.*, 2002). Only then does it become possible for all stakeholders to operate in a converging and complementary manner towards a common goal of transforming the prevailing tillage-based production systems to CA-based systems as a basis for sustainable production intensification. Since to date only about 7 per cent of the world's arable and permanent cropland area is farmed under CA (although more is farmed with no-till only and even more with reduced till), it would appear that in most countries CA is as yet a relatively unknown concept and thus neither the knowledge base nor the other elements of an enabling environment for the adoption of CA in the country exists (Friedrich & Kassam, 2009).

Only on very few occasions has there been rapid adoption, such as in the southern parts of Brazil in the 1990s where problems with conventional tillage-based farming practices had become so severe that a spontaneous change to no-till systems occurred. In this case, uncontrollable water erosion combined with extremely poor profit margins for farmers were the drivers for change. Similarly, it was severe wind erosion in the mid-west USA and the Canadian prairies that led to their adoption of CA. To date erosion problems, climatic problems (drought) and unfavourable profit margins are the most important motivations for farmers to adopt CA. Such problems now exist in many agricultural locations, accompanied by ecosystem degradation, loss of biodiversity, agrochemical overloading and environmental pollution, and loss in agriculture productivity and returns to investment.

The duration of this slow early adoption before it turns into rapid growth can be influenced by a set of necessary conditions. A second related paper (Kassam *et al.*, 2010) elaborates on these requirements for the spread of CA.

Note

1. The views expressed in this paper are those of the authors.

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