Mechanization and the Global Development of Conservation Agriculture[1]

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1. Introduction

The per capita availability of agricultural land was 0.43 ha in 1960 and declined to 0.26 ha in 1999. Significant per capita declines are projected in the availability of another essential natural resource for agriculture - water. At the same time, the world must increase its food production by some 70% by 2050 to meet the needs of its growing population projected to reach 9.2 billion then [Bruinsma, 2003].

There is no alternative but to increase agricultural productivity (i.e. crop yield per unit area) and the associated total and individual factor productivities (i.e. biological output per unit of total production input, and output per unit of individual factors of production such as energy, nutrients, water, labour, land and capital) to meet the global food, feed and biofuel demand and to alleviate hunger and poverty. Thus, feeding the world in 2050 and beyond will need further crop production intensification and optimisation. The type of farm power and farm equipment and machinery has a significant influence on intensification and optimisation outcomes, and on profit. However, until now, agricultural intensification generally has had a negative effect on the quality of many of the essential resources such as the soil, water, land, biodiversity and the ecosystem services which has caused yield and factor productivity growth rates to decline. Another challenge for agriculture is its environmental foot print and climate change. Agriculture is responsible for about 30% of the total greenhouse gas emissions of CO_2, N_2O and CH_4 while being directly affected by the consequences of a changing climate [IPCC, 2007].

The new paradigm of "sustainable production intensification" recognizes the need for a productive and remunerative agriculture which at the same time conserves and enhances the natural resource base and environment, and positively contributes to harnessing the environmental services. Sustainable crop production intensification, which is the new strategic objective A of FAO, must not only reduce the impact of climate change on crop production but also mitigate the factors that cause climate change by reducing emissions and by contributing to carbon sequestration in soils. Intensification should also enhance biodiversity in crop production systems above and below the ground to improve ecosystem services for better productivity and healthier environment. A set of soil-crop-nutrient-water-landscape system management practices, internationally recognized as Conservation Agriculture (CA) delivers on all of these goals. CA saves on energy and mineral nitrogen use in farming and thus reduces emissions; it enhances biological activity in soils, resulting in long term yield and factor productivity increases. Attention to soil health and good soil system management is critical and this message was highlighted in an international Technical Workshop held at FAO headquarters in July 2008 entitled: "Investing in Sustainable Crop Intensification: The Case for Improving Soil Health" [FAO, 2008]. Conservation Agriculture represents a practical concept to achieve improved soil health and better soil-crop-nutrient-water management leading to ecologically and economically sustainable agriculture. The Workshop recommended the mainstreaming of CA internationally and elaborated on the knowledge, policy, institutional and mechanisation support that must be organised to support

[1] The views expressed in this paper are the personal opinion of the authors and do not necessarily quote the official policy of FAO

the uptake and spread of CA. Based on the understanding, that in most agro-ecologies of the world the soil erosion rates by far exceed the soil formation, once the soil surface is mechanically disturbed, there is no truly sustainable agriculture possible based on soil tillage (Montgomery, 2007). CA is a no-tillage-based cropping system, which by synergistic interactions with other crop management techniques overcomes the known limitations of no-tillage when applied as an isolated technique. CA can and should be complemented by other good farming practices for further improvement in the overall performance and resilience of the cropping system.

Conservation Agriculture in the context of sustainable agricultural mechanization is more than just a mechanical technique, such as no-till and direct seeding. It represents a fundamental change in the soil system management and in the cropping system design and management which in turn lead to consequential changes in the required field operations and the related mechanization solutions. When a tillage-based production system is to be transformed into a CA-based system, it involves a shift in the prevailing on-farm mix of mechanical technologies, some of which will remain but with only marginal use in future, and there will be the development of completely new set of mechanical technologies, changes in farm power requirements, and in land use suitability for sustainable intensification as elaborated in the following sections.

2. Conservation Agriculture Globally

2.1. Definition of Conservation Agriculture

According to the World Food and Agriculture Organization, Conservation Agriculture is defined as "*an approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment. CA is characterized by three linked principles, namely:*

1. *Continuous minimum mechanical soil disturbance.*
2. *Permanent organic soil cover.*
3. *Diversification of crop species grown in sequences or associations*."

CA principles are universally applicable to all agricultural landscapes and land uses with locally adapted practices. CA enhances biodiversity and natural biological processes above and below the ground surface. Soil interventions such as mechanical tillage are reduced to an absolute minimum or avoided, and external inputs such as agrochemicals and plant nutrients of mineral or organic origin are applied optimally and in ways and quantities that do not interfere with, or disrupt, the biological processes [FAO 2010].

CA facilitates good agronomy, such as timely operations, and improves overall land husbandry for rainfed and irrigated production. Complemented by other known good practices, including the use of quality seeds, and integrated pest, nutrient, weed and water management, etc., CA is a base for sustainable agricultural production intensification. It opens increased options for integration of production sectors, such as crop-livestock integration and the integration of trees and pastures into agricultural landscapes.

For the purpose of data collection and monitoring these three principles have been quantified as follows:

1. Minimum soil disturbance refers to low disturbance no-tillage and direct seeding. The disturbed area must be less than 15 cm wide or less than 25% of the cropped area (whichever is lower). There should be no periodic tillage that disturbs a greater area

than the aforementioned limits. Strip tillage is allowed if the disturbed area is less than the set limits.

2. Organic soil cover: Three categories are distinguished: 30-60%, >60-90% and >90% ground cover, measured immediately after the direct seeding operation. Area with less than 30% cover is not considered as CA.
3. Crop rotation/association should involve at least 3 different crops. However, repetitive wheat or maize cropping is not an exclusion factor unless it leads to uncontrollable pest and weed problems.

The CA concept and principles of soil-crop-nutrient-water-landscape system management is universally applicable, but it is not a one-size-fit-all ready-to-use blue print recipe for sustainable farming. The actual soil and crop management practices and cropping systems require site specific adaptations and eventually specially designed mechanical technologies and farm power.

2.2. Impact of Conservation Agriculture – cropping systems and environmental services

CA is not a theoretical paper model as it has become a reality on more than 117 million ha around the world with some farms practicing it for over 30 years. Over the past 10 years, the rate of transformation from tillage-based farming to CA has been some 6 million hectares per annum. Several countries have adoption levels of more than 50% of their arable land, which permits the observation of the longer-term and large scale effects of CA on the environment at a landscape or wildlife habitat scale, for example, at watershed or river basin level.

The yield levels of CA systems are comparable with conventional intensive tillage systems, which mean that CA does not lead to yield penalties [DeFelice et al, 2006]. On the contrary, the improved soil health allows better root and plant development and crop health, and leads in the longer term to incremental improvement in yields and factor productivities until a new equilibrium is established. In few cases the change from tillage-based farming to CA can result in modest yield penalties during the first few years for instance due to changes in soil nutrient balance and locking up of nitrogen due to increase in soil microbial activity or in weed infestation. However, there is no inherent systemic reason for such temporary drop in yields. They are generally the result of management errors during the learning and adaptation phase of adoption, which requires changes in all aspects of crop and cropping system management, particularly in fertilizer, pest and weed management regimes [Meyer, 2009]. In situations, where the actual yield levels of tillage-based systems are low compared to the genetic and agroecological potential of the crops, the changeover to CA results in immediate yield increases, particularly in legume crops. This has been the case in most developing countries so far. With this kind of crop response CA fulfils the multiple requirements of sustainable intensification mentioned in the beginning, since it is a production system with a high output potential.

At the same time, CA complies with the generally accepted ideas of sustainability. In the long term the need for fertilizer, compared with tillage-based systems, is reduced due to lower nutrient losses through erosion and leaching and higher availability of soil nutrients to the crops. The soil biological life is stimulated in CA systems, resulting in increased biodiversity below the ground, some of which is responsible for biological nitrogen fixation and nutrient mobilization as well stimulating root and shoot growth, and in biological pest control. Equally the organic mulch cover and diversified crop rotations allow for increased biodiversity above ground including that of predators and parasitoids, resulting in improved pest control, better crop health and an estimated 20% reduction of pesticide use in the long term [Saturnino & Landers, 2002]. The same applies to weed management and herbicide use. During the changeover to CA the herbicide use might remain equal to tillage-based systems, but with a shift in the products used and in their timing of application. However, CA with the application of permanent ground cover, cover crops and diversified crop rotations, together with minimum soil disturbance results, after a transition period of about 2 to 4 years, in a significantly reduced weed pressure with the subsequent reduction in herbicide use [Friedrich, 2005].

Regarding the water resources the mulch cover and the increased soil organic matter levels in CA soils allow a better water retention in the soil in the entire root zone and in improved water use efficiency and crop water productivity, while the improved soil structure, particularly deep reaching continuous macrospores, increases the water infiltration and reduces surface runoff. The recharge of underground aquifers is increased, improving at the same time the water quality due to reduced contamination levels from agrochemicals and soil erosion [Bassi, 2000]. This is of special relevance to improving the resilience of cropping systems under a climate change scenario. Crops within CA systems produce relatively more under drought or excess water conditions and have the potential to save 1,200 km^3/year of water by 2030. It further helps to sequester carbon in soil at a rate of about 0.5 t/ha/year [Reicosky, 2001]; thus the world is sequestering about 60 million tons of carbon per year on the 117 million hectares of arable and permanent crop land that is now under CA.

Also, in socio-economic terms CA systems perform better than tillage-based farming. The production cost and the risk is significantly reduced, which increases farm profits and food security. Labour requirements are reduced by about 50%, and particularly the heavy work of soil tillage and deep cultivation is eliminated [Bishop-Sambrook, 2003]. This allows mechanized farmers to save on labour, fuel and machinery costs. For many farmers in South America the adoption of CA has not been a choice but a question of survival. Farmers with draught animals can complete their farm operations without having to hire tractors for tillage work. Small farmers using manual labour and hand tools can farm more easily, even if their physical strength is limited or reduced due to disease, malnutrition or age, which is the case in many developing countries. The time saving allows such farmers also to dedicate more time to other, more profitable occupations than growing a crop, such as raising livestock, adding value with post harvest processing or seeking off farm employment. In the long term the livelihoods of farmers and rural population are significantly improved [Lange, 2005], resulting in a reduction and even reversal of the rural-urban migration.

2.2. History, development and relevance of CA in developing countries

Tillage, particularly in fragile ecosystems, was questioned for the first time in the 1930s, when the dustbowls devastated wide areas of the mid-west United States. Concepts for reducing tillage and keeping soil covered came up and the term conservation tillage was introduced to reflect such practices aimed at soil protection. Seeding machinery developments allowed then, in the 1940s, to seed directly without any soil tillage. At the same time theoretical concepts resembling today's CA concept were developed by Edward Faulkner who published a book called Ploughman's Folly [Faulkner, 1945] and Masanobu Fukuoka who published a book called One Straw Revolution [Fukuoka, 1975]. But it was not until the 1960s for no-tillage to enter into farming practice in the USA. In the early 1970s no-tillage reached Brazil, where farmers together with scientists transformed the technology into the system which today is called CA. Yet it took another 20 years before CA reached significant adoption levels. During this time farm equipment and agronomic practices in no-tillage systems were improved and developed to optimize the performance of crops, machinery and field operations. From the early 1990s CA started growing exponentially, leading to a revolution in the agriculture of southern Brazil, Argentina and Paraguay. During the 1990s this development increasingly attracted attention from other parts of the world, including development and international research organizations such as FAO, CIRAD and CGIAR. Study tours to Brazil for farmers and policy makers, regional workshops, development and research projects were organized in different parts of the world leading to increased levels of awareness and adoption in a number of African countries such as Zambia, Tanzania and Kenya as well as in Asia, particularly in Kazakhstan and China. The improvement of conservation and no-tillage practices within an integrated farming concept such as of CA led also to increased adoption including in developed countries after the end of the millennium, particularly in Canada, Australia and Finland.

CA crop production systems are experiencing increased interest in most countries around the world. There are only few countries where CA is not practiced by at least some farmers and where there are no local research results about CA available. The total area under CA in 2010 is estimated to be 117 million hectares [Kassam et al., 2010]. CA is now practiced by farmers from the artic circle (e.g. Finland) over the tropics (e.g. Kenya, Uganda), to about 50º latitude South (e.g. Malvinas/Falkland Islands); from sea level in several countries of the world to 3,000 m altitude (e.g. Bolivia, Colombia), from extremely dry conditions with 250 mm a year (e.g. Morocco, Western Australia), to heavy rainy areas with 2,000 mm a year (e.g. Brazil) or 3,000 mm a year (e.g. Chile). No-tillage is practiced on all farm sizes from less than half a hectare (e.g. China, Zambia) to thousands of hectares (e.g. Argentina, Brazil, Kazakhstan). It is practiced on soils that vary from 90% sand (e.g. Australia) to 80% clay (e.g. Brazil's Oxisols and Alfisols). Soils with high clay content in Brazil are extremely sticky but this has not been a hindrance to no-till adoption when appropriate equipment is available. Soils which are readily prone to crusting under tillage farming do not present this problem under CA because the mulch cover avoids the formation of crusts. CA has even allowed expansion of agriculture to marginal soils in terms of rainfall or fertility (e.g. Australia, Argentina). All crops can be grown adequately in CA and to the authors' knowledge there has not yet been a crop that would not grow and produce under this system, including root crops [Derpsch & Friedrich, 2009].

A very special case where CA was introduced under particularly difficult conditions is the Democratic Peoples Republic of Korea. CA was introduced in 2003 with the aim to sustain, secure and eventually intensify agricultural production and to recover at the same time the degraded soil resources. In only a few years CA became national policy supported by the academy of agricultural sciences and heavily requested by farmers. CA adoption spread to more than 30 farms and is applied at approximately 3000 ha. The main bottleneck for further spreading is the availability of suitable equipment, which cannot be manufactured locally. While the introduction started with imported no-till seeders and planters for animal traction, small and medium size tractors from Brazil, some farms at a later stage started to manufacture their own no-till seeders from scrap material and imported no-till seeder components. Starting with upland crops like maize, soya and wheat, the farmers very quickly applied the CA concept to rice, converting it to no-till with residue retention, but without hardpan and permanent flooding, either as no-till transplanted or direct seeded rice. They also applied the concept to potatoes, growing the potato in rotation with rice under a mulch cover of rice straw on the soil surface, eliminating with this the soil disturbance at the potato harvest. Overall farmers and scientists observed after only a few years better soil life and soil organic matter levels, better soil nutrient availability at lower fertilizer requirements and in general a yield increase of more than 10% from the first year on [Kim & Kim, 2008].

The main barriers to the adoption of CA practices continue to be: knowledge on how to do it (know how), mindset (tradition, prejudice), inadequate policies, for example, commodity based subsidies (EU, US) and direct farm payments (EU), unavailability of appropriate equipment and machines (many countries of the world), and of suitable herbicides to facilitate weed and vegetation management (especially in developing countries) [Friedrich & Kassam, 2009].

3. Implications of Conservation Agriculture for agricultural mechanization

3.1 Soil Tillage

The most significant change from tillage-based farming to CA is in the land preparation and seeding practices. The use of tillage as a standard periodic operation is completely eliminated in a fully functioning CA system and remains only for very specific tasks, such as creating the conditions for changing over to CA by breaking up compacted soil or levelling the soil surface. Braking compacted soil may also become necessary within CA system under mechanized farming, particularly in humid climates. In such cases implements with minimum soil disturbance, such as the Paraplow, are preferred. However, the main goal under CA is to avoid soil compaction in the first place for which technical solutions are available. In surface irrigated systems the maintenance of the irrigation furrows between permanent raised beds is a regular operation requiring tillage equipment and in cold moist climates strip tillage before or together with the planting operation can be applied. Overall, the significance of tillage implements in a functioning CA system is reduced drastically.

Conservation Agriculture, and other conservation farming systems, excludes inversion tillage as general practice. There might be still the odd use of ploughs to shape surfaces or as a one-off intervention before starting the systems, but not as regular operation. The same applies to all other forms of tillage. Under conventional agriculture, tillage is considered necessary to create a favourable physical soil structure to enable water infiltration and provide an environment for plants to grow. Optimum soil tilth and aggregate sizes were defined for specific crops, operations and purposes as criteria for the quality of tillage work. Equipment was designed to create different particle sizes in different horizons for the perfect seedbed. However, considering the ability of mechanical soil tillage to create soil structure, it can only reduce aggregate sizes and it can only arrange homogenous aggregates in horizontal layers. This does not really reflect the necessity for a variety of different pore sizes in a well structured soil, which should not be arranged horizontally, but randomly and vertically.

As a consequence in conventional tillage there is usually a distinct separation between the arable horizon and the subsoil. Soil biodiversity and macrofauna populations are reduced in the arable horizon due to intensive tillage, and hardly exist in the subsoil, which is usually a poorly structured dead mineral body with a higher bulk density than the topsoil [Hendrix et al, 1986]. In the worst of cases there is often a compacted layer between the two horizons, resulting from the action of the tillage implements and from traffic. Therefore, water infiltration under conventional tillage takes place mostly in the arable topsoil, while infiltration into the subsoil is reduced. Plant roots prefer the topsoil to grow in as this is rich in nutrients and water and often less dense than the subsoil. This can lead in dry years to water stress as the plant roots are not reaching deeper soil horizons before the topsoil dries out.

Contrary to this CA recognizes that tillage cannot create the ideal soil structure and is not increasing water infiltration, but might be necessary to repair damage. With this understanding any tillage under CA will always be understood as an exceptional intervention, trying to minimize the impact on the soil. Obviously before starting a no-till based CA operation, the field should be in the desired shape, which means levelled or with the desired surface structure, for example beds or ridges. Full tillage is usually necessary to create this surface. But in view of the transition to no-tillage agriculture every effort should be undertaken to avoid excessive destruction of the soil structure or any compaction problems as a result of the land preparation. Subsequently, with few exceptions, tillage will not be undertaken as standard operation under CA.

Ripping is one example of an operation that can become necessary even in CA, particularly during the early transition years on extremely degraded soils in absence of adequate organic matter levels and rooting structures. Rippers are usually designed in a way to create maximum soil disturbance. Often they leave a considerable impact on the surface in the form of clods, calling for secondary tillage operations. Ripping under CA should always try to minimize the impact on the soil and leave few traces on the soil surface. In practical terms ripping should be done at optimum moisture considering the entire profile of the intervention, to avoid excessive clod formation and smeared horizons. The maintenance of the ripper is also important, keeping cutting edges and points sharp. The design of the ripper should avoid lifting clods, which can be achieved, for example, by using rippers with the shanks bent sideward, such as the Paraplow.

Ripping is a costly and not completely risk free operation. Applied in the wrong conditions or without a long term concept for soil structure improvement it can even lead to more serious compaction problems than before the ripping. Therefore ripping will be considered under CA as a temporary feature or exceptional repair operation. In most cases mechanical ripping under CA can be more economically replaced by “biological ripping”, growing crops with specific rooting characteristics. Those crops will be placed within the crop rotations along with cash crops that, mostly due to their harvest, could create soil damage and compaction.

Besides the general repair of soil damage, ripping or other zone-tillage operations could be applied in very specific cases such as wet and cold climates and soils, for transplanting vegetables or for systems where pasture for livestock grazing is included in a crop rotation. In those cases tillage operations will be very time specific and limited in the form of strip tillage, either done in a separate operation or together with planting. Depending on the objective to be obtained, strip tillage can be done with fixed tools like chisels or with driven tools like narrow rotary knife harrows.

Cropping systems involving surface irrigation and bed- or ridge structures might require regular reshaping of the beds. But this intervention usually is only restricted to the furrows, limited in depth and normally not intervening into the growing zones, but in the traffic areas of the system. Reshaping can be combined with the planting operation. The most suitable time for this operation within the cropping cycle also has to be determined with regard to the residue situation. In the long term permanent beds will become more stable and the necessity for reshaping will be less frequent than in the beginning.

3.2 Seeding and planting

Another area of significant change is the seeding and planting operation. Equipment for seeding and planting must be able to deposit the seed with a similar accuracy of conventional seed drills into an untilled soil which ideally is covered with a heavy mulch of crop residues. For this reason the equipment must have specially designed furrow openers which can penetrate the mulch without collecting it or pushing it into the soil and deliver the seed into the soil at the desired depth. In order to do this, no-till direct seeding equipment is usually strong enough to resist the higher soil forces, and heavier than a conventional seed drill, particularly when disk type furrow openers are used. As no-tillage systems such as CA mature and are optimized over a period of time, the trend goes clearly towards minimum disturbance no-till furrow openers, such as double disk, cross slot or star-wheel type tools, which also facilitate weed control management [Desbiolles, 2005].

Conventional concepts for planting consider it necessary to create an optimal seedbed. The seedbed creates controlled conditions, under which the seeding equipment can place the seed with a maximum of precision. Particularly, correct depth placement is of high importance for field emergence and yield of a crop. Obviously the conditions for accurate seeding change dramatically when the seedbed surface is not clean but covered with crop residues. Conditions change completely when the soil as such is not loose and levelled to perfection.

The general idea of creating a seedbed, even in a limited way, is still reflected in many minimum-till- or direct-seeding seed drills. This is particularly the case with power take off driven direct seeding combinations, which in reality do a conventional seedbed preparation before seeding. The only difference is that all operations are done in one pass. In view of the intensive though shallow soil tillage and incorporation of the residues, this technique is not really considered no-till seeding under CA. But also many of the quite popular hoe type direct drills follow this principle. These practices would fall under the category of minimum tillage or conservation tillage farming. From a CA point of view they would still create unnecessary soil movements with the negative implications on weed growth, organic matter decomposition and eventually binding of soil nitrogen, water losses, fuel consumption and last not least increased draft power requirements.

Under Conservation Agriculture the ideal situation would be to place the seed into undisturbed soil which maintains its natural capillary thus minimizing soil water loss at planting [Baker et al. 2007]. By minimizing soil movement and soil exposure to the light outside the mulch cover, the germination of weed seeds is also not stimulated more than necessary. In terms of equipment to be used, the result could also be a “hoe” drill, but rather than being designed for maximum soil movement in the seedbed, it is designed for minimum soil movement resulting in a chisel or knife rather than a wide tine.

Obviously there are different opener types for different soil conditions. But a farmer would normally choose the type which serves as a good compromise for most of the prevailing soil conditions on the farm. No-till seeders and planters are supposed to work in not tilled soils and as a worst case scenario these are considered to be “hard”. For this reason no-till seeders often are heavy, resulting from high mass per seed row to guarantee penetration. This is particularly the case for double disk openers. Under CA there are two points to consider with respect to soil penetration. Provided the soil is kept under a permanent organic cover, it will accumulate organic matter particularly close to the surface. It is expected that with time the planting horizon will soften, requiring less vertical force to penetrate for seed placement. Therefore, depending on the soil type, the requirements for seeders and openers might actually change over the years under CA. After some years of consecutive application of CA, the top layers of the soil acquire a compost-like texture superimposed on the characteristics of the original soil texture and so facilitate planting.

But also the design and choice of openers for a seed drill or planter allows the design of low weight, low draft no till seeders and planters. Those can be pulled by tractors starting from horsepower levels as low as 30 hp while at the same time handling mulch cover and penetrating into untilled soil. To solve this requirement was obviously the precondition to enable small farmers in South America to adopt CA.

The chisel provides the down force facilitating penetration into the soil without the necessity of high equipment mass. The chisel can in this way also facilitate the work of the cutting disk applying additional down force. By design the chisel can still be shaped for minimum soil disturbance. Not only animal traction no till planters are benefiting from this experience. In general it can be noticed that it is also leading to lighter tractor 0-till seeders, allowing for smaller tractors. This becomes obvious by direct comparison of 0-till planters for example from the United States with planters providing similar features from Brazil. As consequence of this strict adherence to CA concepts in machinery design, the Brazilian farmer has the additional benefit of saving on tractor sizes and numbers. A comparable technology of combining a cutting disk for residue handling with the down forces of a chisel, while minimizing soil disturbance, is the cross-slot opener [Baker et al. 2007]. This furrow opener has been specifically designed around the necessity of the seed and the plant. It provides the possibility to place the seed in undisturbed soil with a minimum of visible soil movement.

Compared to the standard hoe drill or sometimes even to a single disk drill, the double disk opener definitively has advantages in terms of soil movement. However, it has disadvantages particularly in very dry and in very wet soil conditions. Despite the problems associated with double disk openers they are probably the most popular no-till planter openers. As such they might be responsible for the perception that no-till planting is associated with higher risk, due to the intolerance of double disk openers to handle unfavourable soil conditions [Baker et al. 2007]. But they are also the reason for the high weight of no-till planters, due to the difficulties to penetrate into hard soils. Ways to improve the performance of double disk openers without giving up the advantages are to offset the two disks or to choose disks of different diameters [Baker et al. 2007]. A combination of both, offset double disks with different diameters are in fact very popular with no-till planter manufacturers in those parts of the world that actually show the highest adoption rates of CA such as the southern parts of South America. The resulting openers provide good penetration, low soil movement and good self cleaning action. Among the equipment operating with double disk furrow openers, the versions with offset disks of different diameters, which is particularly popular in Brazil, is very suited for smaller tractors, since it can cut into most residues and soil conditions with equipment weights of less than 100 kg/row, while other double disk seeders often require weights of 150 to 250 kg/row. Contrary to this manufacturers in the US where adoption of CA has slowed down or in Europe, where adoption is still marginal, offer mostly the standard double disk openers.

In some countries, particularly in Asia, the double disk planters are prohibitively expensive due to the cost for the high quality steel for the disks and the additional weight. Yet, chisel type no-till seeders and planters, as actually favoured in those cases as a low cost equipment, have serious limitations with the residue handling, particularly when seeding small grain cereals like wheat into heavy maize or rice straw residues. The approaches taken so far to solve this problem for smaller tractors are the use of PTO power for strip tilling with narrow rotary harrows to facilitate the penetration through the residues with a light weight seeder (China), or by picking up the residues in front of the furrow opener with a strip-chopper and blowing them on top of the planted row behind the equipment. This type of seeder has been developed in China as well as in the Indo-Gangetic Plains in India and Pakistan where it has become popularly known as the “happy seeder”. It is commercially available in both countries from several manufacturing companies. In general hoe type furrow openers for direct seeding equipment, as often preferred as cheaper options in the early stages of no-tillage, might work well under low residue conditions and with low weed pressures. In general, as CA cropping systems mature and the importance of soil cover through cover crops or residues is appreciated, these furrow openers come to their limits. Also is the relatively high level of soil disturbance leading to unnecessary water losses and weed germination in the seed row. Therefore, in mature CA systems there is a trend to switch to low disturbance furrow openers, most commonly to the various types of disk openers [Ashworth et al., 2010].

One of the most important parameters in seed placement for good emergence and yield is a uniform depth placement. In a conventional seedbed with a loose, uniformly aggregated fine soil surface the planter can shape the seed row and thus create a uniform planting depth not only by controlling the release point but also, if necessary, by levelling the soil surface. Under no-till direct seeding conditions changes in the surface relief are not normally possible. It would anyway be undesirable as soil movement under no-till seeding should be kept to a minimum. The more advanced quality no-till seed drills and no-till planters therefore have independently suspended furrow openers for each row with independent depth control. This feature makes the machines usually more complicated, heavier and more expensive, but it achieves, even under strict no-till planting conditions, uniform seed depth placements. Under practical field conditions in Kazakhstan a seed depth with 90% of the seeds being placed with a tolerance of ± 1 cm could be obtained with furrow openers having independent suspension and depth control, while the rigid furrow openers resulted in a seed depth uniformity of only 67% of the seeds within the same tolerance [Matushkov 2003].

The availability of a suitable no-till planter is often considered to be the largest hurdle in the adoption of CA. Although procuring a no-till planter is not the first step to be undertaken in the adoption of CA, the technology used for planting can have a significant impact on early success or failure of the system. In many cases existing equipment can be adapted at a low cost to perform under no till without sacrificing the quality of the operations. Adaptations of conventional planters and seed-drills to no-till planters have been very popular in Brazil during the early years of the promotion of CA. But even today there are still companies specialized in upgrading old conventional seed drills and planters for no-till use. A similar approach was followed with projects promoting the introduction of CA in Mongolia and, more recently, in Kazakhstan. Often skilled farmers are also able to successfully convert their own planters [Schiffman 1999].

It is difficult enough, particularly for a smaller farmer, to buy a rather expensive new no-till planter, and it might be prohibitive to buy in addition to the no-till row crop planter a no-till seed drill. Over the last few years it could therefore be observed in those regions of the world with the highest CA adoption rates (especially in South America), that most of the established equipment manufacturer offer no-till planters and seed drills that can be converted from row crop planting to no till seeders for small grain crops.

3.3 Weed and residue management

Equipment for weed management remains partly unchanged under CA system. While cultivators and hoe type equipment loose importance in CA systems, slashers, cutters or crimper-rollers are used for mechanical surface weed management. Chemical herbicide applicators play a significant role, whereas wick type and low volume applicators (CDA) provide chances to reduce the water volumes significantly. Sprayers remain the main tool for herbicide application and precision tools like sensors detecting weeds and switching the corresponding nozzles on or off, can significantly contribute to reduce the use of herbicides, particularly when weeds only appear in certain spots. However, contrary to tillage-based systems, weed management in CA does not necessarily aim at complete elimination or removal of weeds. Important point here is that weeds are not allowed to multiply or interfere with the crop growth. Some cover crops that are nowadays used in CA were previously considered as weeds.

The harvest operation in CA is part of the land preparation for seeding the next crop. The management of crop residues during the harvest has direct influence on ease, problems and quality of the subsequent planting operation. Standing residues, anchored in the soil, or at least tall standing stubble can facilitate seeding particularly in high or difficult residue situations, such as in the case of high yielding rice. In semi-arid continental climates with winter precipitation and extremely low winter temperatures, a standing residue or high stubble facilitates the trapping of snow and hence water retention [Fileccia, 2009]. In other conditions anchored residues or high stubble might avoid that the residue mulch is washed away by rain- or irrigation water and collects in lower parts of the field, or blown away by windstorms. Another important aspect is the treatment of the residues. In tillage-based systems the fast decomposition of residues is desired to facilitate incorporation and mineralization in the soil. Hence residues are mostly chopped. Under CA the integrity of the residues as soil cover is important. Hence, the retention and even the spreading of un-chopped residues are preferred. Depending on the type of residues and furrow openers, this also facilitates the subsequent seeding compared to chopped residues. Farmers practicing CA often use simple residue spreaders, which can be attached to the combine harvesters, rather than choppers, which has the additional benefit of a lower energy requirement. However, a still unsolved limitation is the throwing width for unchopped straw. An even distribution is only possible up to 4-5 m header width. One of the most important tools specific to CA, and which is used for residue, cover crop and weed management especially in sub-humid or humid climates, is the knife roller, crop crimper or vegetation crusher. It is also used in organic no-till farming, which essentially is CA without the use of synthetic agro-chemicals.

Residue retention in CA is an issue in many countries since residues are often used as animal feed or more recently as bio-energy feedstock. The integration of crop and livestock production is therefore an important issue. Forage production as part of the crop rotation with forage, cover or relay crops will have to be inserted in the cropping system, and the grazing or withdrawal of residues for forage purposes will have to be controlled to strike a compromise between feeding the soil and feeding the livestock. Obviously also in such areas there will be options for equipment and technological solutions, starting from forage cutting and collecting equipment to controlled grazing equipment, such as solar powered electric fences.

Another significant change that is taking place is in the farm power requirements. Without the heavy tillage operation, the required peak farm power on a farm is roughly halved. In mechanized systems the overall power requirement for tractors decreases by about 50% with an additional shift towards lower horsepower by about 40%. For a farmer switching completely to CA system, there would be significantly lower amount of capital tied up in farm machinery [Bistayev, 2002].

3.4 Avoiding soil compactions

Soil compaction is another point of discussion for no-tillage systems. Soils that are not tilled tend to support more weight, resulting in better trafficability. However, this also has limits. In a no-till farming system the repair of soil damage such as compaction is extremely expensive – because it is not foreseen – and maximum care should be taken to avoid compaction problems in the first place. This is best done by controlling the traffic, choosing suitable tyres or tracks but also, depending on soil type and climate, limiting the maximum mass of machinery. It might prove more economical to use two smaller units rather than one big unit if in this way compaction can be kept at a tolerable level.

The best option seems to restrict any traffic to limited areas of the field and not to allow any traffic at all on the cropping areas. Field results show that a 15% loss of surface can be compensated in such a system by the yield increase in the never compacted areas [Kerr 2001]. However, ideally the traffic areas are kept at a minimum between 10 or 15% of the surface. Controlled traffic systems are not yet very common in most parts of the world. But in combination with no-till farming systems such as CA they make even more sense [Gaffney and Wilson 2003]. In addition to this they are very easy to introduce in cropping systems using permanent rows or beds and even in flat field crops they do not create a major hurdle in times of commercially available GPS technologies. It is important that all traffic at all times is restricted to the same tracks. Broadcast crops would usually require the use of differential

GPS tracking systems which allow the permanent tracks to be found with accuracy in the cm-range even when they are not visible in the field.

The strict application of controlled traffic for all operations provides a chance for the introduction of CA even in large scale, heavy mechanized farming and in crops, in which some field operations have to be carried out under wet soil conditions which invariably would lead to compaction. Examples could be pest control operations in cotton under tropical climatic conditions or harvest operations in crops like sugar cane or sugar beet, or in wet years even the normal grain crop or silage harvest. From the machine side this approach would require basic design changes, as the high equipment masses, for example of self propelled harvesters, could not be supported anymore across the working width with flotation or with multiple tyres, but they would have to be supported along the track with a footprint as narrow and as long as possible (Fig. 6). Since the rubbertrack technology is fairly advanced this should be technically possible but it is not yet realized to a sufficient extent in commercially available machinery (Fig. 7). However, recently some manufacturers have appeared on the market, for example with self propelled sprayers, adding a third axle and using narrow high tyres rather than flotation tyres to support the machinery weight.

Controlled traffic farming is increasingly gaining popularity in Australian CA farms, but also in mechanized no-till farms in Africa and Central Asia, using satellite based guidance and eventually auto-steer options. In permanent bed systems, a special form of Conservation Agriculture systems, for example under furrow irrigation, controlled traffic can be applied even without any guidance systems since all crops in the rotations are planted on the same beds.

3.5 Opportunities for new technology developments

While some common farm equipment, such as tillage equipment, looses importance when changing from tillage-based farming to CA systems, other new equipment, such as the knife roller and residue spreaders, are introduced, offering new opportunities for technology development. The consequent application of CA will also lead to modifications in the design of some existing equipment. Root crop harvesters will have to reduce the impact on soil structure, as for example puller type opposed to digger type peanut harvesters, or they will have to operate in a completely different environment, such as in case of the mulch potato which so far is commercially grown only in areas using hand harvest.

4. Policy and institutional support implications for developing countries

Due to the benefits of CA in combining a high output intensive production with sustainability and improved environmental services, policy makers are increasingly becoming interested in harnessing the potential of CA systems. Yet, for the successful introduction and up scaling of CA in a country, the availability and accessibility of equipment and machinery for CA is often one of the biggest impediments. Suitable policies would need to facilitate capital access for farmers and eventually even directly subsidize the cost of the equipment and machinery to reduce the investment risk for early adopters. This “subsidy” could be justified as payment for environmental services, considering the reduced impact on the environment from CA compared to tillage-based farming. But even with adequate capital, farmers in most countries would not be able to source suitable equipment. To address this problem the market needs to be stimulated, import taxes for equipment and raw material need to be adjusted to facilitate the import and eventually national manufacturing of CA equipment. As long as no national producer of equipment is servicing the farmers, existing suppliers from other countries need to be proactively brought into the country, including facilitating the building up of dealership and service networks.

Mechanization policies need to be coherent with CA policies. This would mean that the standard equipment for a tractor would not be the plough or the disk harrow but a no-till seeder. Also the reduced farm power requirements under CA need to be considered when planning a national mechanization strategy. Considering also the other savings, for example in tillage equipment, the overall investment requirements for complete replacement or renewal programmes on farm mechanization can be reduced by 50% compared to tillage-based systems [Bistayev, 2002]. This was of relevance for example in the countries of the former Soviet Union which after independence were left with mostly obsolete machinery in need of complete replacement. By reducing the overall demand for farm power, the change to CA is not necessarily a threat to the agricultural machinery industry because it could facilitate the opening up of new markets or new equipment options. In this regard, there is a need for local manufactures and equipment suppliers to provide support in supplying seeders and other equipment that would normally not be available in rural outlets. However, in some world regions farm machinery industry is among the strongest opponents and stumbling blocks for the scaling of full CA in fear of their tractor and tillage equipment sales.

Ultimately, it must be recognised that a behavioural change in all stakeholders must be encouraged and facilitated to help the changeover to CA system. This includes the role and competences of the key national extension, research and education institutions, the government departments, development agencies and donors that support them, as well as the private sector including farmers and farm managers who have an important and often unique role to play in innovation processes and in input supply markets including for equipment and machinery.

CA is knowledge intensive with many new aspects and those who must promote it or practice it require training and practical experience. In the case of farmers, an opportunity to test, learn and adapt is necessary. For extension staff and NGO staff, training is necessary in alternative mechanization technologies. Similarly, in universities and national and international research institutions, there is a need to include training and research on CA-related agronomy and cropping system management at the field, farm and landscape level, as well on the equipment options for different situations.

5. Conclusions

Considering the current world challenges posed by increasing demand for food, feed, fibre and biofuel from crop production, ecological and economic sustainability has to be considered in any intensification and productivity enhancement strategy. Hence, innovations for sustainable agricultural mechanization can only be meaningful and effective within the context of sustainable crop production systems, and never in isolation. Conservation Agriculture includes the basic elements of such a sustainable production system, increasing productivity and production while reducing the need for external inputs and the environmental footprint of farming. CA improves the delivery by agriculture of ecosystem services such as water resources, biodiversity and the mitigation of climate change while strengthening the ecological foundation of cropping systems to also adapt to changing climates. Conservation Agriculture requires adequate and very specific mechanization inputs which could be described as “innovations for sustainable agricultural mechanization”, while some of the currently used and promoted technologies will be reduced due to their negative impact on the environment and society. Conservation agriculture is practiced in 2010 on about 117 million ha worldwide, growing exponentially at a rate of actually 6 million ha/year.

Yet, to become fully sustainable, the socioeconomic component of the production system as well as the mechanization structure has to be considered. Improved profitability of farming and farmers' livelihoods form an economic base that also allows the mechanization sector to develop and prosper in a sustainable way. In many developing countries, especially in Africa, supportive and guiding policies are required to attract and encourage the agricultural machinery sector to open up and develop markets for agricultural mechanization in general and for CA equipment in particular and to establish the required commercial and service infrastructures. Without this change in the machinery sector, future agriculture development needs of developing countries for food security, poverty alleviation, economic growth and environmental services cannot be achieved.

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