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Conservation Agriculture, Improving Soil Quality for Sustainable Production Systems?

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7.1 INTRODUCTION

7.1.1 Food Production and Land Degradation

Human efforts to produce ever-greater amounts of food leave their mark on our environment. Persistent use of conventional farming practices based on extensive tillage, especially when combined with removal or in situ burning of crop residues, have magnified soil erosion losses and the soil resource base has been steadily degraded (Montgomery 2007). Many soils have been worn down to their nadir for most soil parameters essential for effective, stable and sustainable crop production, including soil physical, chemical and biological factors. Kaiser (Science 11 June 2004 p 1617) summarized the effect of land degradation on crop production. Lester Brown (as cited by Kaiser 2004) estimated that human activity was responsible for the loss of 26 billion tons of topsoil per year, 2.6 times the natural rate. Pimentel et al. (1995) estimated that in the United States erosion inflicted $44 billion a year in damage to farmland, waterways, infrastructure, and health. He predicted that if farmers failed to replace lost nutrients and water, U.S. crop yields would drop 8% per year. Even in high yielding areas where soils are not considered to be degraded, crops require an ever-increasing input to maintain yields. Despite the availability of improved varieties with increased yield potential, the potential increase in production is generally not attained because of poor crop management (Reynolds and Tuberosa 2008). Another direct consequence of farmers' persistent use of traditional production practices is rapidly increasing production costs associated with the inefficient use of inputs whose costs continue to rise. In addition, any new, more sustainable management strategy must be compatible with emerging crop diversification policies that may evolve to meet new consumer or industrial requirements. All of this must be accomplished within a scenario of decreasing area available for crop production because of urbanization and industrial expansion and the recent dramatic increases in the use of land for biofuel and industrial crop production, instead of for food.

7.1.2 Conservation agriculture

Nowadays, people have come to understand that agriculture should not only be high yielding, but also sustainable (Reynolds and Borlaug 2006). Farmers concerned about the environmental sustainability of their crop production systems combined with ever-increasing production costs have begun to adopt and adapt improved system management practices which lead to the ultimate vision of sustainable agriculture. Conservation agriculture has been proposed as a widely adapted set of management principles that can assure more sustainable agricultural production. The name conservation agriculture has been used to distinguish this more sustainable agriculture from the narrowly-defined 'conservation tillage' (Wall 2007). Conservation tillage is a widely-used terminology to denote soil management systems that result in at least 30% of the soil surface being covered with crop residues after seeding of the subsequent crop (Jarecki and Lal 2003). To achieve this level of ground cover, conservation tillage normally involves some degree of tillage reduction and the use of non-inversion tillage methods. Conservation agriculture removes the emphasis from the tillage component alone and addresses a more enhanced concept of the complete agricultural system. It combines the following basic principles:

1. Reduction in tillage: The objective is to achieve zero tillage, but the system may involve controlled tillage seeding systems that normally do not disturb more than 20-25% of the soil surface;
2. Retention of adequate levels of crop residues and soil surface cover: The objective is the retention of sufficient residue on the soil to protect the soil from water and wind erosion; to reduce water run-off and evaporation; to improve water productivity and to enhance soil physical, chemical and biological properties associated with long term sustainable productivity. The amount of residues necessary to achieve these ends will vary depending on the biophysical conditions and cropping system.
3. Use of crop rotations: The objective is to employ diversified crop rotations to help moderate/mitigate possible weed, disease and pest problems; to utilise the beneficial effects of some crops on soil conditions and on the productivity of subsequent crops; and to provide farmers with economically viable cropping options that minimize risk.

These conservation agriculture principles are applicable to a wide range of crop production systems from low-yielding, dry, rainfed conditions to high-yielding, irrigated conditions. However, the techniques to apply the principles of conservation agriculture will be very different in different situations, and will vary with biophysical and system management conditions and farmer circumstances. Specific and compatible management components (pest and weed control tactics, nutrient management strategies, rotation crops, appropriately-scaled implements etc.) will need to be identified through adaptive research with active farmer involvement. For example, under gravity-fed irrigated conditions, a permanent raised-bed system with furrow irrigation may be more suitable and sustainable than a reduced or zero tillage system on “the flat” to replace the widely used, conventionally tilled system of flood irrigation on flat land. Permanent raised beds are not tilled but only reshaped as needed between crop cycles. One to four rows are planted on top of the bed, depending on the bed width and crop, with irrigation applied in the furrow. Residues are chopped and left on the surface.

Applying conservation agriculture essentially means altering literally generations of traditional farming practices and implement use. As such, the movement towards conservation agriculture-based technologies normally is comprised of a sequence of step-wise changes in cropping system management to improve productivity and sustainability. The principles of marked tillage reductions are initially applied in combination with the retention of sufficient amounts of crop residue on the soil surface, with the assumption that appropriate crop rotations can be maintained or incorporated into the system later to achieve an integrated, sustainable production system. It is unlikely that complex, multi-component technologies such as conservation agriculture can be successfully scaled out through traditional linear models of research and extension: instead they require the development of innovation systems to adapt technologies to local conditions (Wall et al. 2002). Experience in commercial and non-commercial farming systems show that it is essential that an innovation systems approach includes functioning networks of farmer groups, machinery developers, extension workers, local business and researchers (Hall et al. 2005). For this purpose, decentralized learning hubs within different farming systems and agro-ecological zones should be developed (Sayre and Govaerts 2009). In these hubs, an intense contact and exchange of information is organized between the different partners in the research and extension process. Because of the multi-faceted nature of conservation agriculture technology development and extension, activities should be concentrated in a few defined locations representative of certain farming systems rather than have lower intensity efforts on a wide scale. Through the research and training, regional conservation agriculture networks are established to facilitate and foment research and the extension of innovation systems and technologies. The hubs are directly linked to the strategic science platforms operated by international centers and national research institutes to permit the synthesis and global understanding of conservation agriculture, and its adaptability to different environments, cropping systems and farmers’ circumstances.

7.1.3 Soil quality

When evaluating an agricultural management system for sustainability, the central question is: Which production system will not exhaust the resource base, will optimize soil conditions and will reduce food production vulnerability, while at the same time maintaining or enhancing productivity? Soil quality can be seen as a conceptual translation of the sustainability concept towards soil. Karlen et al. (1997) defined soil quality for the Soil Science Society of America as ‘the capacity of a specific kind of soil to function, within natural managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation’. A simpler operational definition is given by Gregorich et al. (1994) as ‘The degree of fitness of a soil for a specific use’. This implies that soil quality depends on the role for which the soil is destined (Singer and Ewing 2000). Within the framework of agricultural production, high soil quality equates to the ability of the soil to maintain a high productivity without significant soil or environmental degradation. Evaluation of soil quality is based on physical, chemical and biological characteristics of the soil. With respect to biological soil quality, a high quality soil can be considered a ‘healthy’ soil. A healthy soil is defined as a stable system with high levels of biological diversity and activity, internal nutrient cycling, and resilience to disturbance (Rapport 1995). Management factors that can modify soil quality include tillage and residue management systems, as well as the presence and conformation of crop rotations (Karlen et al. 1992). Changes in soil quality are not only associated with management, but also with the environmental context, such as temperature and precipitation (Andrews et al. 2004).

A comparative soil quality evaluation is one in which the performance of the system is determined in relation to alternatives. The biotic and abiotic soil system attributes of alternative systems are compared at some time. A decision about the relative sustainability of each system is made based on the difference in magnitude of the measured parameters (Larson and Pierce 1994). A comparative assessment is useful for determining differences in soil attributes among management practices that have been in place for some period of time (Wienhold et al. 2004). In a dynamic assessment approach the dynamics of the system form a meter for its sustainability (Larson and Pierce 1994). A dynamic assessment is necessary for determining the direction and magnitude of change a management practice is having (Wienhold et al. 2004), especially when compared to the common, existing farmer practices and it must be understood that this assessment normally must involve an adequate time frame.

7.2 INFLUENCE OF CONSERVATION AGRICULTURE ON PHYSICAL SOIL QUALITY

7.2.1 Soil structure and aggregation

Soil structure is a key factor in soil functioning and is an important factor in the evaluation of the sustainability of crop production systems. Emerson (1959) defines soil structure as the size, shape and arrangement of solids and voids, continuity of pores and voids, their capacity to retain and transmit fluids and organic and inorganic substances, and the ability to support vigorous root growth and development, to which we would add their ability to permit the diffusion of gases, especially oxygen and carbon dioxide. Soil structure is often expressed as the degree of stability of aggregates (Bronick and Lal 2005). Soil structural stability is the ability of aggregates to remain intact when exposed to different stresses (Kay et al. 1988) and measures of aggregate stability are useful as a means of assessing soil structural stability. Shaking of aggregates on a wire mesh both in air (dry sieving) and in water (wet sieving) are commonly used to measure aggregate stability (Kemper and Rosenau 1986). With dry sieving the only stress applied is the one from the sieving, while with wet sieving the samples are additionally exposed to slaking. Therefore, the mean weight diameter (MWD) of aggregates after dry sieving is generally larger than MWD after wet sieving.

7.2.1.1 Influence of tillage

Zero tillage with residue retention improves dry aggregate size distribution compared to conventional tillage (Govaerts et al. 2009a, 2007c). The effect on water stability of aggregates is even more pronounced, with an increase in MWD of wet sieving reported for a wide variety of soils and agro-ecological conditions (Govaerts et al. 2009a, 2007c, Lichter et al. 2008, Li et al. 2007, Pinheiro et al. 2004, Chan et al. 2002, Filho et al. 2002, Hernanz et al. 2002, Carter 1992a). Even when conventional tillage results in a good structural distribution, the structural components are weaker to resist water slaking than in zero tillage situations with crop residue retention, where the soil becomes more stable and less susceptible to structural deterioration. The reduced aggregation in conventional tillage is a result of direct and indirect effects of tillage on aggregation (Beare et al. 1994, Six et al. 1998). Physical disturbance of soil structure through tillage results in a direct breakdown of soil aggregates and an increased turnover of aggregates (Six et al. 2000) and fragments of roots and mycorrhizal hyphae, which are major binding agents for macroaggregates (Bronick and Lal 2005, Tisdall and Oades 1982). The aggregate formation process in conventional tillage is interrupted each time the soil is tilled with the corresponding destruction of aggregates. The residues lying on the soil surface in conservation agriculture protect the soil from raindrop impact. No protection occurs in conventional tillage, which increases susceptibility to further disruption (Six et al. 2000). Moreover, during tillage a redistribution of the soil organic matter takes place. Small changes in soil organic carbon can influence the stability of macro-aggregates. Carter (1992a) found a close linear relationship between organic carbon and MWD. Soil organic matter can increase both soil resistance and resilience to deformation (Kay 1990, Soane 1990), and improve soil macroporosity (Carter et al. 1990). Higher organic matter content in the topsoil reduces slaking and disintegration of aggregates when they are wetted (Blevins et al. 1998). Tillage reduces macrofauna populations in comparison with conservation agriculture systems (Kladivko 2001) decreasing the potentially positive effect of macrofauna on soil aggregation (Six et al. 2004).

7.2.1.2 Influence of residue management

Since organic matter is a key factor in soil aggregation, the management of previous crop residues is a key to soil structural development and stability. It has been known for many years that the addition of organic substrates to soil improves its structure (Ladd et al. 1977). Fresh residue forms the nucleation centre for the formation of new aggregates by creating hot spots of microbial activity where new soil aggregates are developed (De Gryze et al. 2005, Guggenberger et al. 1999). Denef et al. (2002) found that adding wheat (*Triticum aestivum* L.) residue in the laboratory to three soils differing in weathering status and clay mineralogy increased both unstable and stable macroaggregate formation in all three soils in the short term (42 days). The greatest response in stable macroaggregate formation occurred in soils with mixed mineralogy (a mixture of 2:1 and 1:1 clays as opposed to soils dominated by 2:1 or 1:1 clays). This could be a result of electrostatic bondings occurring between 2:1 clays, 1:1 clays and oxides (i.e. mineral-mineral bindings), in addition to the organic matter functioning as a binding agent between 2:1 and 1:1 clays. The return of crop residue to the soil surface does not only increase the aggregate formation, but it also decreases the breakdown of aggregates by reducing erosion and protecting the aggregates against raindrop impact. The MWD of aggregates as measured by dry and wet sieving decreased with decreasing amounts of residues retained in a rainfed permanent bed planting system in the subtropical highlands of Mexico, although partial residue removal by baling kept aggregation within acceptable limits (Govaerts et al. 2007c). This indicates that it is not always necessary to retain all crop residues in the field to achieve the benefits of permanent raised beds or zero tillage systems. Similar results were obtained by Limon-Ortega et al. (2006) on permanent raised beds in an irrigated system, where the aggregates showed the largest dispersion where residue was burned and the lowest where all residue was kept in the field. Chan et al. (2002) also found that stubble burning significantly lowered the water stability of aggregates in the fractions >2 mm and < 50 µm.

7.2.1.3 Influence of crop rotation

Altering crop rotation can influence soil organic carbon by changing quantity and quality of organic matter input (Govaerts et al. 2009b) and thus has the potential to alter soil aggregation indirectly. Few studies report on the influence of crop rotation on soil aggregation. Arshad et al. (2004) investigated the effect of the type of break crop in a wheat-based system on aggregation of an Albic Luvisol in the cold, semiarid region of northwestern Canada. Three rotations were included in the study (wheat–wheat–fallow, wheat–wheat–canola [*Brassica campestris* L.], and wheat–wheat–pea [*Pisum sativum* L.]).There were no significant differences in soil-structural properties among the various annual cropping systems. Similarly, Filho et al. (2002) did not find any significant differences in aggregate stability between three crop rotations (soyabean-wheat-soyabean [*Glycine max* (L.) Merr.], maize [*Zea mays* L.]-wheat-maize and soyabean-wheat-maize) on an Oxisol in Brazil. Hernanz et al. (2002) reported inconsistent effects of crop rotation on water stability of aggregates in a Vertic Luvisol. Monoculture of winter wheat or barley (*Hordeum vulgare* L.) resulted in greater aggregate stability than did winter wheat and vetch (*Vicia sativa* L.) rotation, but the effect was only significant in some size fractions.

Crops can affect soil aggregation by their rooting system because plant roots are important binding agents at the scale of macroaggregates (Six et al. 2004, Thomas et al. 1993). Lichter et al. (2008) found significantly more large macroaggregates in a soil under a wheat crop than in a soil under a maize crop. Wheat has a more horizontal growing root system than maize and the plant population of wheat is higher resulting in a denser superficial root network. This denser root network could positively influence aggregate formation and stabilization (Denef and Six 2005, Six et al. 2004). Also, soil microbial biomass and bacterial diversity can influence aggregate formation (Six et al. 2004) and these can be influenced by crop rotation.

7.2.2 Soil porosity

Pores are of different size, shape and continuity and these characteristics influence the infiltration, storage and drainage of water, the movement and distribution of gases, and the ease of penetration of soil by growing roots. Pores of different size, shape and continuity are created by abiotic factors (e.g. tillage and traffic, freezing and thawing, drying and wetting) and by biotic factors (e.g. root growth, burrowing fauna) (Kay and VandenBygaart 2002). Pore characteristics can change in both space and time following a change in tillage practices. These changes primarily reflect changes in the form, magnitude and frequency of stresses imposed on the soil, the placement of crop residues and the population of microorganisms and fauna in the soil (Kay and VandenBygaart 2002).

7.2.2.1 Bulk density and total porosity

Total porosity is normally calculated from measurements of bulk density so the terms bulk density and total porosity can be used interchangeably (Kay and VandenBygaart 2002). The effect of tillage and residue management on soil bulk density is mainly confined to the topsoil (plough layer). In deeper soil layers, soil bulk density is generally similar in zero and conventional tillage (D'Haene et al. 2008, Gál et al. 2007, Blanco-Canqui and Lal 2007, Thomas et al. 2007, Hernanz et al. 2002, Yang and Wander, 1999). A plough pan may be formed by tillage immediately underneath the tilled soil, causing higher bulk density in this horizon in tilled situations (Dolan et al. 2006, Yang and Wander 1999).

A reduction in tillage would be expected to result in a progressive change in total porosity with time, approaching a new 'steady state'. However, initial changes may be too small to be distinguished from natural variation (Kay and VandenBygaart 2002). Logsdon and Karlen (2004) measured bulk density in the 0-30 cm layer of three deep-loess, field-scale watersheds located in western Iowa. Measurements were taken five times in the four years following conversion of two of the three watersheds from conventional to zero tillage. The third watershed was maintained using ridge-tillage and continuous maize. There were no significant differences in soil bulk density between the two watersheds converted to zero tillage or between them and the ridge-tillage watershed in the sampling period. Al-Kaisi et al. (2005) found similar bulk density values under chisel ploughing and zero tillage three and seven years after implementation of zero tillage on Mollisols in Iowa.

The results of the effects of different tillage practices on bulk density in experiments that have run for approximately 10 years are variable. Horne et al. (1992) measured increases in bulk density under zero compared with conventional tillage (mouldboard plough) after 10 years in an imperfectly drained, loess soil in New Zealand. Hernanz et al. (2002) determined bulk density at the end of the growing season in a Vertic Luvisol with a loam texture in the semiarid conditions of central Spain, 13 years after the start of the experiment. They found significantly higher bulk density under zero than under conventional tillage from 0-10 cm with cereal monoculture and from 0-15 cm in a wheat-vetch (*Vicia sativa* L.) rotation, but the more compacted topsoil with zero tillage had no adverse effect on crop yield with either rotation. Bulk density was greater under zero than under conventional tillage in the top 8 cm of an eroded silt loam in southern Illinois (Hussein et al. 1998) and in the top 10 cm of a Luvisol in southern Queensland (Thomas et al. 2007). Bulk density was lower, however, with zero tillage than with conventional tillage at a depth of 3–7 cm and not different in the 13-17 cm layer in a loam in southeast Norway (Ekeberg and Riley 1997). Bulk density was similar or lower in the 5–10 cm soil layer under minimum tillage than under conventional tillage on silt loam soils with crop rotations (including root crops) in Belgium (D'Haene et al. 2008). Yang and Wander (1999) found lower bulk density values with zero tillage than with mouldboard tillage in the 0-5 cm and 20-30 cm layer, higher values in the 5-20 cm layer and similar values in the 30-90 cm layer.

Differences in total porosity between tillage comparisons on the longer term (≥15 years) have been somewhat more consistent. On a silt loam with a maize-soyabean rotation in Minnesota, soil bulk densities were higher in the surface layer of zero tillage than conventional tillage after 23 years, but lower below 30 cm, reflecting the rupture action of tillage near the surface and the compacting and shearing action of tillage implements below tillage depths (Dolan et al. 2006). Similarly, Gál et al. (2007) observed higher bulk density in the 0-30 cm layer under zero than under conventional tillage on a silty clay loam in Indiana after 28 years, but no difference in the 30-100 cm layer. In a side-by-side comparison of zero and mouldboard tillage for 19 years across a variable-landscape in southern Ontario, bulk density measured before spring tillage was dependent upon depth and tillage. Averaged across soil textures varying from sandy loam to clay loam, bulk density was greater under zero than under mouldboard tillage in the top 20 cm of the soil profile with the greatest difference at 5–10 cm. Organic matter content at 0–5 cm was greater under zero than under mouldboard tillage which probably helped diminish the difference in total porosity (Kay and VandenBygaart 2002). Similar results were obtained by Deen and Kataki (2003). Tebrügge and Düring (1999) found that the average bulk density from 0 to 24 cm was greater under zero than under conventional tillage at five different field sites in Germany that had been under a tillage comparison for 10–18 years. However, when only the top 3 cm was considered, the bulk density was lower under zero tillage, which was attributed to the development of an organic-rich mulch and possibly enhanced faunal activity. Li et al. (2007) compared the long-term effects of zero tillage with residue retention and conventional tillage without residue in a 15-year field experiment on the loess plateau of northern China. During the first 6 years of the experiment, soil bulk density to 20 cm depth was significantly less in the conventional treatment, demonstrating the increase in bulk density which occurred in the zero tillage treatments, probably caused by wheel traffic and lack of regular soil loosening. In the following 5 years, however, mean soil bulk densities of the two treatments were similar, and in the last 2 years, bulk density became slightly less in the zero tillage with residue retention treatment than in conventional tillage, suggesting that the traffic effect on bulk density had been negated and a new equilibrium had been reached with the improvements in soil condition, including improved soil organic carbon, increased biotic activity, and improved structure.

The impact of a reduction in tillage on total porosity may be influenced, in part, by the magnitude of axle load of equipment, timing of traffic and degree of control of traffic. Inconsistent effects of a reduction in tillage on the variation in total porosity with depth may be related to differences in traffic on different sites, or on soil quality at the time tillage was reduced or stopped. As the resilience of soils to compression and compaction is a function of soil organic matter content and aggregate stability, the effect of reducing compressive forces on soils is likely to depend on the soil quality at the transition. It is very difficult to assess this possibility since researchers seldom report information on traffic during the tillage trials (Kay and VandenBygaart 2002). However, the importance of traffic on porosity differences among tillage systems is illustrated in traffic control experiments. For instance, Logsdon et al. (1999) found no significant difference in bulk density under chisel plough and zero tillage when traffic was not controlled in two fine silty loess soils in the mid-western US during 1–3 years after tillage and traffic were initiated. However, when traffic was controlled and the non-trafficked areas were sampled, bulk density was lower under zero tillage than under chisel plough in the top 5 cm, but greater at 6–18 cm depth.

In summary, the introduction of zero tillage can result in the loss of total pore space as indicated by an increase in bulk density. However, the loss of porosity is generally limited to the plough layer. There is some evidence that the porosity in the top 5 cm of the profile may be greater under zero tillage. The extent of increase may be a function of the build-up of organic matter at this depth and enhanced macrofaunal activity. The adoption of controlled traffic when converting to zero tillage is important in limiting the possible loss of pore pace.

In soils that shrink and swell, the total porosity varies with water content and the assessment of the impact of changes in tillage practice on total porosity requires the determination of the influence of tillage on their shrinkage curves (McGarry 1988). Chan and Hulugalle (1999) reported that compaction increased (i.e., specific volume of air-filled pores in oven-dried clods decreased) in two irrigated Vertisols in the 4 years after conversion from conventional to permanent raised beds. They hypothesized that the lack of controlled traffic and the low soil faunal populations due to the low air porosities in irrigated Vertisols and the high rate of agro-chemical application contributed to the increase in compaction. The same trend was observed for dryland Vertisols with cotton-based crop rotations (Hulugalle et al. 2007).

Reports on the effect of crop rotation and residue management on soil porosity are sparse. Chang and Lindwall (1992) determined the effect of various wheat-based rotations (continuous winter wheat, winter wheat-summer fallow, and winter wheat-barley-summer fallow) on bulk density of a Brown Chemozemic loam under zero and conventional tillage. After 8 years, no significant effect of crop rotation on bulk density was found in either tillage system. Hulugalle et al. (2007) reported that compaction increased in dryland Vertisols with cotton-based crop rotations after conversion from conventional to permanent raised beds. This compaction was less under rotations which included a wheat crop (cotton [*Gossypium hirsutum* L.]-wheat, cotton-wheat double cropped and cotton-chickpea [*Cicer arietinum* L.] double cropped followed by wheat). Al-Kaisi et al. (2005) measured bulk density in different crop rotations under zero tillage on a soil association including Mollisols and Entisols. The three treatments included smooth bromegrass (*Bromus inermis* Leyss.) (grazed continuously for two months each year), switchgrass (*Panicum virgatum* L.) (grazed on a rotational basis every 3 weeks for 5 months each year), and maize–soyabean–alfalfa (*Medicago sativa* L.) (one maize season followed by one soyabean season and three consecutive seasons of alfalfa). After 10 years, bulk density was significantly lower in the smooth bromegrass treatment than in the maize-soyabean-alfalfa treatment in the 0-15 and 15-30 cm layer. After 12 years of zero tillage, cropping systems that returned more crop residue (continuous cropping and wheat-maize-fallow or wheat-sorghum [*Sorghum bicolor* (L.) Moench.]-fallow) decreased bulk density and increased total and effective porosities compared with a wheat-fallow system (Shaver et al. 2002).

Blanco-Canqui and Lal (2007) measured bulk density in zero tillage plots that had been uncropped and receiving three levels of wheat straw mulch (0, 8, and 16 Mg ha^{-1} yr^{-1}) for 10 consecutive years on a silt loam in central Ohio. Straw management had a large impact on bulk density in the 0-10 cm depth. Differences in bulk density among the treatments were not significant in the 10-20 cm depth. The bulk density under the high-mulch treatment was 58% lower and that under the low-mulch treatment was 19% lower than the bulk density under the unmulched treatment for the 0-3 cm depth. In the 3-10 cm depth, bulk density under the high-mulch treatment was only 36% lower and that under the low-mulch treatment was 9% lower than under the control. These results are similar to those reported by Lal (2000), who observed that annual application of 16 Mg ha^{-1} of rice (*Oryza sativa* L.) straw for 3 years decreased bulk density from 1.20 to 0.98 Mg m^{-3} in the 0-5 cm layer on a sandy loam. Similarly, Blanco-Canqui et al. (2006) reported that maize residue retention at 5 and 10 Mg ha^{-1} for a period of one year reduced bulk density in the 0-5 cm layer from 1.42 Mg m^{-3} (control) to 1.26 and 1.22 Mg m^{-3}, respectively, in zero tillage systems in a silt loam. Treatments of conventional tillage, chisel tillage and zero tillage, all with either residue returned or harvested, were imposed on a silt loam soil with a maize-soyabean rotation in Minnesota (Dolan et al. 2006). Treatments where residue was harvested had 6% higher bulk density in the 0–5 and 5–10 cm soil depths than the treatments with residue returned. The trend was reversed in the 30–45 cm soil depths, where the treatments with residue returned had 5% higher bulk density than the treatments where residues were harvested. All these studies indicate that the retention of crop residue in the field is important to prevent compaction when conventionally tilled fields are converted to zero tillage.

7.2.2.2 Pore size distribution and pore continuity

The changes in total porosity introduced by management are related to alterations in pore size distribution. Total porosity of soils is distributed among different pore size classes and different size classes fulfil different roles in aeration, infiltration, drainage and storage of water, and offer different mechanical resistance to root growth (Kay and VandenBygaart 2002). Numerous criteria have been used to define pore size classes, complicating comparisons between the results of different authors. Kay and VandenBygaart (2002) use three classes (macro-, meso- and micropores) that are distinguished in their functional relation to soil water. Pores with diameters >30 μm are referred to as macropores. Water flows primarily through these pores during infiltration and drainage and consequently these pores exert a major control on soil aeration. In addition, much of root growth is initiated in these pores. Pores with an equivalent diameter of 0.2–30 μm are referred to as mesopores, and are particularly important for the storage of water for plant growth. Micropores have effective diameters <0.2 μm. Water in these pores is generally not available to plants and their small diameter precludes microbiological activity. Lipiec et al. (2006) associated peaks in the pore size distribution with the organization of the porous system in a matrix (textural) domain and secondary (structural) domain. Textural porosity results from the fabric of elementary solid particles, and is subject to swelling and shrinkage. Structural porosity consists of voids created by aggregate and clod arrangement due to tillage, climate and biological pores (Guérif et al. 2001).

7.2.2.2.1 Micro- and mesopores

In general, micro- and mesoporosity is reported to be higher in zero compared to conventional tillage, but in some cases no effect of tillage is observed. The volume of pores <14 μm was significantly higher under zero than under conventional tillage in both silt loam and sandy loam gray Luvisols of the northwestern Canadian prairies (Azooz and Arshad 1996). The volume fraction of pores 0.2–60 μm diameter in a coarse sandy soil from Scandinavia was greater under zero than under conventional tillage at depths of 5–10 and 15–20 cm at the end of 6 years (Rasmussen 1999). Greater proportions of mesopores (equivalent diameter of 0.2–10 μm) were found under zero tillage than under mouldboard and chisel plough at a depth of 0–15 cm in an eroded silt loam from Illinois (Hussein et al. 1998). The volume fraction of pores <30 μm diameter at a depth of 5–19 cm in a silt loam from Maryland was not different between tillage practices at the end of 10 and 11 years (Hill 1990). Also Yoo et al. (2006) did not find any effect of tillage on the volume of micro- and mesopores (<15 μm) in two silt loam soils and a silty clay loam in Illinois.

Almost no reports on the influence of residue management and crop rotation on pore size distribution were found, although Blanco-Canqui and Lal (2007) found a higher volume of mesopores (5-25 μm) in the 0-3 cm layer in zero tillage with residue retention than in zero tillage without residue retention.

7.2.2.2.2 Macropores

Macropores are important for water flux and infiltration in both saturated (Lin et al. 1996) and unsaturated conditions (Deeks et al. 1999). In addition, a soil matrix with macro-pores offers greater potential for undisturbed root growth because the roots can bypass the zones of high mechanical impedance (Lipiec and Hatano 2003). Disturbance of soil by primary or secondary tillage would be expected to result in a loosening of soil and thus an increase in the macroporosity of the tilled zone. When soils are converted to zero tillage, macroporosity would be expected to be limited in the zone that was formerly tilled due to processes such as traffic-induced compaction. However, this compaction may be compensated by progressive creation of macropores from roots and faunal activity with time (Kay and VandenBygaart 2002). Macropores that are vertically oriented are more persistent under traffic than horizontal pores (Blackwell et al. 1990). Many of these pores would be biopores and would extend well below the zone of tillage.

The commonly observed decrease in total porosity in zero tillage relative to conventional tillage is associated with significant changes in pore size distribution in the macropore class. As the number of years in zero tillage increased from 4 to 11 years, there was a decrease in the number of pores 30–100 μm equivalent diameter in the top 20 cm of silt loam soils in southern Ontario (VandenBygaart et al. 1999). Schjønning and Rasmussen (2000) determined macroporosity in three soils, a coarse sandy soil, a sandy loam and a silty loam. Generally the zero tillage treatment had a lower volume of macropores (>30 μm) in the 4-8 and 14-18 cm depths than the mouldboard tillage treatment. An exception was the 14-15 cm depth of the sandy loam soil where the opposite was found, presumably due to a plough pan. Yoo et al. (2006) did not find consistent results at three locations in Illinois (two with a silty clay loam and one with a silt loam soil). At one of the three locations (the silt loam soil), the volume of small macropores (15–150 μm), as well as large macropores (>150 μm) was smaller under zero than under conventional tillage. At the other two locations, either small macroporosity (in the silt loam) or large macroporosity was smaller under zero tillage (in the silty clay loam). In the 0-5 cm layer of a 24 years old experiment on a Paleustalf in Australia, the volume of pores >60 μm was significantly greater (more than 11%) under zero tillage with residue retention than under conventional tillage with residue burnt (Zhang et al. 2007). A silt loam from Kentucky under zero tillage for 17 years contained less macroporosity (>50 μm) than under conventional tillage at each of three depths (0–5, 10–15 and 20–25 cm), yet the average pore size was significantly larger under zero tillage (Drees et al. 1994). Blanco-Canqui and Lal (2007) found that the >50-μm pores in the mulched treatments were about twice the volume of those in the unmulched control in the 0-3 cm layer on a silt loam in central Ohio.

Water infiltration, retention, and flow do not only depend on the quantity and size of pores but also on the interconnectivity and shape of pores (Bouma and Anderson 1973). Changes in the morphology of pores reflect changes in the processes that create these pores. Irregular and elongated shaped pores >1000 μm in diameter and length, respectively, are greater in number in conventional relative to minimum tillage at a depth of 0–20 cm and can be attributed to the annual mixing and homogenization by the plough (Kay and VandenBygaart 2002). VandenBygaart et al. (1999) found that pores 100–500 μm equivalent diameter increased in number after only 4 years of zero tillage, primarily due to the rounded pore morphology class. They speculated that the increase in this size class and type was due to the maintenance of channels created by wheat and maize roots, whose modal size tend to lie in this size class. A greater proportion of macropores oriented in the horizontal direction in the 5–15 cm depth under zero tillage than under conventional tillage was observed, which the authors attributed to the formation and thawing of ice lenses: under conventional tillage these features would be destroyed annually with tillage.

Biopores created by roots and fauna such as earthworms can be maintained in the plough layer in the absence of annual tillage. Generally these are rounded pores >500 μm observed in thin sections (Kay and VandenBygaart 2002). VandenBygaart et al. (1999) found that rounded biopores increased with zero tillage duration. After 6 years, more biopores >500 μm were present in zero tillage than in tilled systems although the total number of pores >1000 μm was much greater under conventional tillage. They attributed this to the maintenance of root and earthworm channels under zero tillage throughout the years, while these are destroyed annually under conventional tillage. Van Drees et al. (1994) found interconnection of fine macropores (50-100 μm) throughout the profile in zero tillage soil. Earthworm channels with excrement infillings were abundant in the zero tillage plots at all depths, but absent in conventionally tilled plots. Eynard et al. (2004) observed more very fine tubular macropores (<1000 μm) in zero tillage than in tilled Ustolls, indicating increased biological activity in pore formation.

7.2.3 Hydraulic conductivity and water-holding capacity

Hydraulic conductivity would be expected to be higher in zero tillage with residue retention compared to conventional tillage due to the larger macropore conductivity as a result of the increased number of biopores that is commonly observed (Eynard et al. 2004, McGarry et al. 2000, VandenBygaart et al. 1999, Van Drees et al. 1994). However, reported results are not consistent. This might be partly due to difficulty in measuring hydraulic conductivity when a residue cover is present in zero tillage. The presence of residue complicates the installation of measurement instruments or the removal of undisturbed samples and cores, and may cause high variation in conductivity values at small scales (cm) due to macropores and other structural attributes that are left intact by the absence of tillage (Strudley et al. 2008). Also differences in soil sampling depth, amount of straw mulch, and site-specific characteristics (e.g., soil texture, slope, tillage) between studies may explain inconsistencies in the observed effects of tillage on hydraulic conductivity and water-holding capacity (Blanco-Canqui and Lal 2007).

Azooz and Arshad (1996) found that both the saturated and unsaturated hydraulic conductivities were higher under zero tillage conditions than under conventional tillage on two Luvisols (silty loam and sandy loam soils). Chan and Heenan (1993) found that, despite similar bulk density, hydraulic conductivity under ponded infiltration of zero tillage with residue retention was 1-4 times that of conventional tillage with residues burnt, suggesting the presence of significantly more transmitting macropores under zero tillage with residue retention. However, measuring ponded infiltration with traditional double ring infiltrometers is not recommended for comparing tillage systems because of the disruption of the surface soil which may impose major differences on infiltration rates. Liebig et al. (2004) reported that after 15 years of zero tillage with continuous cropping on a silt loam soil in the Great Plains of the USA, saturated hydraulic conductivity was higher than in the conventional tillage crop-fallow system. Blanco-Canqui and Lal (2007) reported that saturated hydraulic conductivity was 123 times greater in the top 3 cm of zero tilled soil that had received 8 or 16 Mg wheat straw ha^{-1} yr^{-1} for 10 consecutive years compared to zero tilled soil that had not received straw. Sharratt et al. (2006) reported that zero tillage almost doubled saturated hydraulic conductivity compared to conventional tillage (disking in autumn and spring) in the surface 0-10 cm soil depth after 20 years on a loam or sandy loam in subarctic Alaska. They found no significant changes in saturated hydraulic conductivity with straw management (removal or retention). Horne et al. (1992) did not find significant differences in the saturated hydraulic conductivities of soil cores taken from the top 10 cm of zero and mouldboard tilled plots of an imperfectly drained, loess soil under a maize-oats (*Avena sativa* L.) rotation in New Zealand. After 8 years, the saturated hydraulic conductivity of zero tillage soil was less than that of conventional tillage soil in the tillage zone and greater below the tillage zone on a Brown Chemozemic loam (Chang and Lindwall 1992). Singh and Malhi (2006) reported after six years of different tillage and residue management practices on a Black Chernozem and a Gray Luvisol in a cool temperate climate in Alberta, Canada, that in the Black Chernozem the steady-state infiltration rate was significantly lower (33%) under zero tillage than under rototillage. Residue retention improved the steady-state infiltration rate in both zero tillage and rototillage. However, in a Gray Luvisol, the same authors found that the steady-state infiltration rate was not significantly affected by tillage and residue management.

Soil management practices that increase the organic matter content of the soil could have a positive impact on the soil water holding capacity (Hatfield et al. 2001). Hudson (1994) showed that over a wide range of soils, there was an increase in water availability with increases in soil organic matter. Consequently, conservation agriculture has the potential to increase water holding capacity. At ten locations in Belgium on silt loam soils, the water content at saturation was higher for reduced compared to conventional tillage (D'Haene et al. 2008). Blanco-Canqui and Lal (2007) found that straw mulching increased the soil's capacity to retain water at all soil water potentials (0 to −1500 kPa) in the top 10 cm of a silt loam soil in Central Ohio, but had no effect in the 10-20 cm layer.

7.2.4 Soil water balance

7.2.4.1 Infiltration and runoff

In spite of the inconsistent results on the effect of tillage and residue management on soil hydraulic conductivity, infiltration is generally higher in zero tillage with residue retention compared to conventional tillage and zero tillage with residue removal. This is probably due to the direct and indirect effect of residue cover on water infiltration. Soil macroaggregate breakdown has been identified as the major factor leading to surface pore clogging by primary particles and microaggregates and thus to formation of surface seals or crusts (Le Bissonnais 1996, Lal and Shukla 2004). The presence of crop residues over the soil surface prevents aggregate breakdown by direct raindrop impact as well as by rapid wetting and drying of soils (Le Bissonnais 1996). Moreover, aggregates are more stable under zero tillage with residue retention compared to conventional tillage and zero tillage with residue removal (Govaerts et al. 2009a, 2007c, Li et al. 2007, Pinheiro et al. 2004, Chan et al. 2002 Filho et al. 2002, Hernanz et al. 2002, Carter 1992a). Under these conditions wind erosion and rapid wetting (i.e. slaking) cause less aggregate breakdown, preventing surface crust formation (Lal and Shukla 2004, Scopel and Findeling 2001, Le Bissonnais 1996). In addition, the residues left on the topsoil with zero tillage and crop retention act as a succession of barriers, reducing the runoff velocity and giving the water more time to infiltrate. The residue intercepts rainfall and releases it more slowly afterwards. The 'barrier' effect is continuous, while the prevention of crust formation probably increases with time (Scopel and Fideling 2001). This was confirmed by the results of Ball et al. (1997) who found greater infiltration rates in zero tillage with residue retention after 26 years than after 9 years.

McGarry et al. (2000) conducted rainfall simulator tests on Vertisols and concluded that the time-to-pond, final infiltration rate and the total infiltration were significantly larger with zero tillage with residue retention than with conventional tillage. They ascribed this to the abundance of apparently continuous soil pores from the soil surface to depth under zero tillage as opposed to a high-density surface crust in conventional tillage found in an image analysis of the different soils. In the highlands of Mexico, higher direct infiltration rates were recorded in zero tillage with residue retention than under conventional tillage, although the infiltration rate in conventional tillage was considerably higher than zero tillage without residue retention (Govaerts et al. 2009a). Similar results were obtained in bed planting systems in the same area (Govaerts et al. 2007c). Also Roth et al. (1988) reported that soil with 100% soil cover facilitated complete infiltration of a 60 mm rainfall, whereas only 20% of rain infiltrated when the soil was bare. In the northern Great Plains, Pikul and Aase (1995) found that infiltration rates were higher when the soil surface was protected: infiltration over a 3 h period was 52 mm in conventional tillage with a wheat-fallow rotation and 69 mm in an annually cropped system with zero tillage. In a 24 year-old experiment on a Paleustalf in Australia, the infiltration rate under zero tillage with residue retention was 3.7 times that of conventional tillage with residue burnt Zhang et al. (2007). Baumhardt and Lascano (1996) reported that mean cumulative rainfall infiltration was the lowest for bare soil and increased curvilinearly with increasing residue amounts on a clay loam, but additions above 2.4 Mg ha^{-1} had no significant effect because of sufficient drop impact interception. The corollary of the higher infiltration with residue cover is a concomitant reduction in runoff (Rhoton et al. 2002, Silburn and Glanville 2002, Rao et al. 1998).

7.2.4.2 Evaporation

Soil evaporation is determined by two factors: how wet the soil is and how much energy the soil surface receives to sustain the evaporation process (Hsiao et al. 2007). Tillage moves moist soil to the surface, increasing losses to drying (Hatfield et al. 2001). Blevins et al. (1971) and Papendick et al. (1973) showed that tillage disturbance of the soil surface increased soil water evaporation compared to untilled areas. The total soil water evaporation fluxes in Iowa were 10 to 12 mm for a 3-day period following each cultivation operation in the spring, while the total evaporation fluxes from zero tillage fields were <2 mm over this same period (Hatfield et al. 2001). The amount of energy the soil surface receives is influenced by canopy and residue cover. Greb (1966) found that residue and mulches reduce soil water evaporation by reducing soil temperature, impeding vapour diffusion, absorbing water vapour onto mulch tissue, and reducing the wind speed gradient at the soil–atmosphere interface. Sauer et al. (1996) reported that the presence of residue on the surface reduced soil water evaporation by 34 to 50%. Dahiya et al. (2007) found that mulching decreased soil water loss on average by 0.39 mm d^{-1} compared to the unmulched control during the two weeks after wheat harvest on a loess soil in Germany. The rate of drying is determined by the thickness of the residue together with the atmospheric evaporative potential (Tolk et al. 1999). Residue characteristics that affect the energy balance components (e.g. albedo and residue area index) and have a large impact on evaporation fluxes vary throughout the year and spatially across a field because of the nonuniform distribution of residue (Sauer et al. 1997). Unger and Parker (1976) and Steiner (1989) concluded that residue thickness (volume) is more important than mass per unit area for controlling evaporation.

7.2.4.3 Soil water content and plant available water

Conservation agriculture can increase infiltration and reduce runoff and evaporation compared to conventional tillage and zero tillage with residue removal. Consequently, soil moisture is conserved and more water is available for crops. Azooz and Arshad (1995) found higher soil water contents under zero tillage compared with mouldboard plough in British Columbia. Johnson et al. (1984) reported that more soil water was available in the upper 1 m under zero tillage compared with other tillage practices in Wisconsin. Mupangwa et al. (2007) determined the effect of mulching and tillage on soil water content in a clay and a sand soil in Zimbabwe. Mulching helped conserve soil water in a season with long periods without rain at both experimental sites. Soil water content consistently increased with increase in surface cover across the three tillage practices (planting basins, ripper tine and conventional plough). Soils under zero tillage with residue retention generally had higher surface soil water contents compared to tilled soils in the highlands of Mexico (Govaerts et al. 2009a). Gicheru et al. (1994) showed that crop residue mulching resulted in more moisture down the profile (0-120 cm) throughout two crop periods (the short rains and the long rains) during two years than conventional tillage and tied ridges in a semi-arid area of Kenya. More soil water enables crops to grow during short-term dry periods. Blevins et al. (1971) reported that short periods of drought stress occurred in crops growing on ploughed soils whereas none occurred in zero tillage with residue retention. Therefore, zero tillage with residue retention decreases the frequency and intensity of short midseason droughts (Bradford and Petersen 2000). Thus, tillage and residue management may significantly affect crop yields during years of poor rainfall distribution (Johnston and Hoyt 1999).

7.2.5 Soil erosion

Erosion rates from conventionally tilled agricultural fields average 1-2 orders of magnitude greater than erosion under native vegetation, and long-term geological erosion exceeds soil production (Montgomery 2007). Soil erosion is a function of erosivity and erodibility. Erosivity is related to the physical characteristics of the rainfall at the soil surface and runoff velocity. It is therefore affected by crop residues that break the raindrop impact and slow down runoff, reducing erosion. Erodibility of the soil is related to the physical features of the soil (Blevins et al. 1998). Aggregate breakdown is a good measure for soil erodibility, as breakdown to finer, more transportable particles and microaggregates increases erosion risk (Le Bissonais 2003). Consequently, the higher aggregate stability in conservation agriculture practices as compared to conventionally tilled fields or zero tillage fields without residue retention results in lower soil erosion potential in conservation agriculture (Govaerts et al. 2007c, Li et al. 2007, Pinheiro et al. 2004, Chan et al. 2002, Filho et al. 2002, Hernanz et al. 2002, Carter 1992a). The positive effect of conservation agriculture on reduced erodibility is further enhanced by the reduced amount of runoff (Rao et al. 1998, Rhoton et al. 2002). After 24 years, zero tillage with stubble retention significantly reduced runoff and soil erosion hazards compared to conventional tillage with stubble burnt, due to the higher soil aggregate stability and higher macroporosity of the surface soil (Zhang et al. 2007). Richardson and King (1995) reported that tillage practice had no effect on surface runoff amounts in watersheds with heavy clay soils in central Texas but that zero tillage with residue retention reduced the loss of sediment, N, and P relative to conventional tillage. Schuller et al. (2007) used cesium-137 measurements to document changes in the rate and extent of soil erosion associated with the shift from conventional tillage to a zero tillage system on a farm in south-central Chile with a temperate climate and a mean annual precipitation of 1100 mm year^{-1}. The implementation of zero tillage practices with residue retention coincided with a reduction in the net erosion rate by about 87% and the proportion of the study area subject to erosion from 100% to 57%. On a sloping field in Japan, soil loss with zero tillage farming combined with a mucuna cover crop (*Mucuna pruriens* (L.) DC) was only 3% of that for the conventional tillage farming with natural fallow (Nagumo et al. 2006). In summary, conservation agriculture results in erosion rates much closer to soil production rates than conventional tillage and therefore could provide a foundation for sustainable agriculture (Montgomery 2007).

The susceptibility of soils to wind erosion largely depends on the aggregate size distribution (Zobeck and Popham 1990) and is determined by dry sieving (Chepil 1962). The percentage of aggregates with sizes smaller than 0.84 mm is considered the soil fraction susceptible to be transported by wind (Chepil 1942). Hevia et al. (2007) found this erodible fraction to be 20% of the total sample weight in zero tillage and 49% in conventional tillage in an Entic Haplustoll of Argentina, showing that the conventional tillage soil was more susceptible to wind erosion. Moreover, a time-dependent trend toward an increase of the proportion of aggregates retained on an 0.84 mm mesh and a decrease in the proportion of aggregates >19.2 mm in conventional tillage indicated that tillage was degrading aggregates >19.2 mm into smaller aggregates. In zero tillage the erodible fraction remained almost unchanged between sampling dates. Singh and Malhi (2006) reported similar results after six years of different tillage and residue management practices on a Black Chernozem in a cool temperate climate in Alberta, Canada. The wind-erodible fraction (measured as dry aggregates < 1 mm size) was smallest (18%) under zero tillage with residue retention and largest (39%) under conventional tillage (rototilling) with residue removal. Zero tillage with residue removal and conventional tillage with residue incorporation showed intermediate results. Vegetation and crop residue cover also play an important role in decreasing wind erosion by reducing the exposure of soil to wind at the surface and intercepting saltating material. Standing stubble is more effective in controlling wind erosion than flattened stubble (Hagen 1996).

7.2.6 Soil temperature

The energy available for heating the soil is determined by the balance between incoming and outgoing radiation. Retained residue affects soil temperature close to the surface because it affects this energy balance. Solar energy at the soil surface is partitioned into soil heat flux, sensible heat reflection, and latent heat for water evaporation (Bristow 1988). Surface residue reflects solar radiation and insulates the soil surface (Chen and McKyes 1993, Shinners et al. 1994). The heat flux in soils depends on the heat capacity and thermal conductivity of soils, which vary with soil composition, bulk density, and water content (Hillel 1998, Jury et al. 1991). Because soil particles have a lower heat capacity and greater heat conductivity than water, dry soils potentially warm and cool faster than wet soils. Moreover, in wet soils more energy is used for water evaporation than warming the soil (Radke 1982). Tillage operations increase the rates of soil drying and heating because tillage disturbs the soil surface and increases the air pockets in which evaporation occurs (Licht and Al-Kaisi 2005).

Soil temperatures in surface layers can be significantly lower (often between 2 and 8 °C) during daytime (in summer) in zero tilled soils with residue retention compared to conventional tillage (Johnson and Hoyt 1999, Oliveira et al. 2001). In these same studies, during night the insulation effect of the residues led to higher temperatures so there was a lower amplitude of soil temperature variation with zero tillage. Dahiya et al. (2007) compared the thermal regime of a loess soil during two weeks after wheat harvest between a treatment with wheat straw mulching, one with rotary hoeing and a control with no mulching and no rotary hoeing. Compared to the control, mulching reduced average soil temperatures by 0.74, 0.66, 0.58 °C at 5, 15, and 30 cm depth respectively, during the study period. The rotary hoeing tillage slightly increased the average soil temperature by 0.21 °C at 5 cm depth compared to the control. The tillage effect did not transmit to deeper depths. Gupta et al. (1983) also found that the difference between zero tillage with and without residue cover was larger than the difference between conventional tillage (mouldboard ploughing) and zero tillage with residue retention. Both mouldboard ploughing and zero tillage without residue cover had a higher soil temperature than zero tillage with residue cover, but the difference between mouldboard ploughing and zero tillage with residue cover was approximately one-third the difference between zero tillage with and without residue.

In tropical hot soils, mulch cover reduces soil peak temperatures that are too high for optimum growth and development to an appropriate level, favouring biological activity, initial crop growth and root development during the growing season (Acharya et al. 1998, Oliveira et al. 2001). In temperate areas, however, lower temperatures create unfavourable cool soils slowing down early crop growth and leading to crop yield declines, especially if late frosts occur (Kaspar et al. 1990, Schneider and Gupta 1983). Aston and Fischer (1986) and Cutforth and McConkey (1997) showed that the soil temperature regime for wheat grown under standing stubble differed from that for wheat grown after conventional cultivation, and suggested that temperature could be at least partly responsible for the observed growth lag. Similarly, Kirkegaard et al. (1994) observed lower daytime soil temperatures in zero tillage when stubble was retained and suggested that this might be partly responsible for the reduced wheat growth and rooting depth observed for this practice. Azooz et al. (1997) proposed the creation of a residue-free band without soil disturbance centred over maize rows, alternated with a residue strip in between rows, as an alternative practice to provide more heat input into the soil surface at the row centre. The soil surface heat flux and soil temperature in the zero tillage practice with a 30 cm residue-free strip were not different from a conventional tillage system and significantly higher than in zero tillage without residue-free strip. The 30 cm residue-free strip did not have a negative impact on soil water content of the top 5 cm layer (depth), where the plant seeds are located. These results indicated that a residue-free strip over the row centre could be important in temperate areas. Similar results were obtained by Kaspar et al. (1990) who showed that removing maize residue from the seedbed increased the emergence rate. Licht and Al-Kaisi (2005) found that soil temperature increased in the top 5 cm under strip tillage (1.2-1.4 °C) compared to zero tillage and that it remained close to soil temperature with chisel ploughing on Mollisols in Iowa, but this change in soil temperature was not reflected in improvement of plant emergence rate index or maize grain yield.

7.3 INFLUENCE OF CONSERVATION AGRICULTURE ON CHEMICAL SOIL QUALITY

7.3.1 Soil organic carbon

Measures of soil quality in agricultural land can include, besides measures of soil physical quality, factors linked to soil chemical quality such as pH, nitrogen levels, exchangeable cations, salinity, toxic chemicals and soil organic carbon (Hulugalle et al. 2002b, Karlen et al. 1992).Soil organic carbon (SOC) has been proposed as a primary indicator of soil quality (Conteh et al. 1997, Reeves 1997), especially the SOC concentration of surface soil (Franzluebbers 2002). The surface soil is the vital horizon that receives much of the seed, fertilizers and pesticides applied to cropland. It is also the layer that is affected by the intense impact of rainfall, and that partitions the flux of gases into and out of the soil. Surface organic matter is essential to erosion control, water infiltration, and conservation of nutrients.

7.3.1.1 Total soil organic carbon content

When comparing SOC in different management practices, several factors have to be taken into account. As reported earlier, bulk density can be affected by tillage practices. If bulk density increases after conversion from conventional tillage to zero tillage, and if samples are taken to the same depth within the surface soil layer, more mass of soil will be taken from the zero tillage soil than from the conventionally tilled soil. This could increase the apparent mass of SOC in the zero tillage and could widen the difference between the two systems if there is significant SOC beneath the maximum depth of sampling (VandenBygaart and Angers 2006). Therefore, Ellert and Bettany (1995) suggested basing calculations of SOC on an equivalent soil mass rather than on genetic horizons or fixed sampling depths in order to account for differences in bulk density. Tillage practice can also influence the distribution of SOC in the profile with higher SOC content in surface layers with zero tillage than with conventional tillage, but a higher content of SOC in the deeper layers of tilled plots where residue is incorporated through tillage (Jantalia et al. 2007, Gál et al. 2007, Thomas et al. 2007, Dolan et al. 2006, Yang and Wander 1999, Angers et al. 1997). Consequently, SOC contents under zero tillage compared with conventional tillage can be overstated if the entire plough depth is not considered (VandenBygaart and Angers 2006). Baker et al. (2007) state that not just the entire plough depth, but the entire soil profile should be sampled in order to account for possible differences in root distribution and rhizodeposition between management practices.

7.3.1.1.1 Influence of tillage practice on soil organic carbon

Govaerts et al. (2009b) report on a literature review to determine the influence of the different components comprising conservation agriculture (reduced tillage, crop residue retention and crop rotation) on SOC. In 7 of 78 cases, the SOC content was lower in zero compared to conventional tillage; in 40 cases it was higher and in 31 of the cases there was no significant difference (Govaerts et al. 2009b). The mechanisms that govern the balance between increased, similar or lower SOC after conversion to zero tillage are not clear. Although more research is needed, especially in the tropical areas where good quantitative information is lacking, some factors that play a role can be distinguished.

Differences in root development and rhizodeposits— Crop root-derived C may be very important in contributing to SOC (Holanda et al. 1998; Flessa et al. 2000; Gregorich et al. 2001; Baker et al. 2007) and a reduction of tillage can influence root development.

Soil bulk density and porosity—Yoo et al. (2006) concluded that the use of zero tillage practices only enhances physical protection of SOC where soil bulk density is relatively high (approximately 1.4 g cm^{-3}) and when the use of zero tillage management reduces the volume of small macropores (15–150 μm), thought to be important for microbial activity (Strong et al. 2004). There may be a threshold value for bulk density that must be exceeded before pore-dependent processes are constrained and protect SOC (Yoo et al. 2006).

Climate— Ogle et al. (2005) found that management impacts were sensitive to climate in the following order from largest to smallest changes in SOC: tropical moist > tropical dry > temperate moist > temperate dry. The biochemical kinetics of the processes involved with (1) the breakdown of soil organic matter (SOM) following cultivation, (2) the formation of aggregates in soils after a change in tillage, and (3) the increased productivity and C input with the implementation of a new cropping practice, are likely to occur at a more favourable rate under the temperature regimes of tropical regions and in more moist climatic conditions. In turn, this leads to a larger change in SOC (Ogle et al. 2005).

The stabilization of C in micraggregates-within-macroaggregates— Occluded intra-aggregate particulate organic matter C in soil microaggregates contributes to long-term soil C sequestration in agricultural soils (Six et al. 2004). Microaggregates-within-macroaggregates constitute relatively stable and secluded habitats for microorganisms, when compared to microaggregate outer surfaces or macroaggregates as a whole (Mummey et al. 2004). Denef et al. (2007) suggested that enhanced C and N stabilization within the microaggregate-within-macroaggregate fraction under permanent raised beds compared to conventionally tilled raised beds was related to the dynamic behaviour rather than the amount of the microaggregates (and the macroaggregates that protect them). In other words, the differences in the amount and concentration of C of microaggregates-within-macroaggregates between management systems can be linked to differences in amount and stability, as well as the turnover, of the microaggregates-within-macroaggregates.

7.3.1.1.2 Influence of residue retention on soil organic carbon

Crop residues are precursors of the SOC pool, and returning more crop residues to the soil is associated with an increase in SOC concentration (Dolan et al. 2006, Wilhelm et al. 2004, Paustian et al. 1997, Rasmussen and Parton 1994). Blanco-Canqui and Lal (2007) assessed long-term (10 year) impacts of three levels (0, 8, and 16 Mg ha^{-1} on a dry matter basis) of wheat straw applied annually on SOC under zero tillage on a Aeric Epiaqualf in central Ohio. Overall, SOC from 0 to 50 cm depth was 82.5 Mg ha^{-1} in the unmulched soil, 94.1 Mg ha^{-1} with 8 Mg ha^{-1} mulch, and 104.9 Mg ha^{-1} with 16 Mg ha^{-1} mulch.

The rate of decomposition of crop residues depends not only on the amount retained, but also on soil characteristics and the composition of the residues. The composition of residues left on the field—the soluble fraction, lignin, hemic (cellulose) and polyphenol content—will determine its decomposition (Sakala et al. 2000, Vanlauwe et al. 1994, Palm and Sanchez 1991, Trinsoutrot et al. 2000). The soluble fraction is decomposable (Sakala et al. 2000) and can stimulate the decomposition of the (hemi)cellulose (Vanlauwe et al. 1994). Lignin is resistant to rapid microbial decomposition and can promote the formation of a complex phenyl-propanol structure, which often encrusts the cellulose-hemicellulose matrix and slows decomposition of these components (Sanger et al. 1996).

7.3.1.1.3 Influence of crop rotation on soil organic carbon

Altering crop rotation can influence SOC by changing the quantity and quality of organic matter input (Govaerts et al. 2009b). Increased moisture conservation related to conservation agriculture practices (Govaerts et al. 2009a, Sommer et al. 2007) can result in the possibility of growing an extra cover crop right after the harvest of the main crop. Cover crops lead to higher SOC contents by increasing the input of plant residues and providing a vegetal cover during critical periods (Franzluebbers et al. 1994; Bowman et al. 1999), but the increase in SOC concentration can be negated when the cover crop is incorporated into the soil (Bayer et al. 2000). Replacement of fallow with legume ‘green manures’ such as lentil (*Lens culinaris* M.) and red clover (*Trifolium pratense* L.) appears to be an effective practice in Canada where they increase SOC concentrations (VandenBygaart et al. 2003). The inclusion of a green-manure or cover crop is, however, only a feasible option in regions without a prolonged dry season (Jantalia et al. 2007). Conservation agriculture can increase the possibility for crop intensification due to a faster turn around time between harvest and planting. Moreover, other cropping options may become available since the actual growing period can be increased by the decreased turnaround time (Erenstein and Laxmi 2008) and the enhanced soil water balance. In some situations it may be possible to include an extra crop in the system after the main crop, or by intercropping or relay cropping with the main crop (Jat et al. 2006).

From a global database of 67 long-term experiments West and Post (2002) calculated that enhancing rotation complexity (i.e., changing from monoculture to continuous rotation cropping, changing crop–fallow to continuous monoculture or rotation cropping, or increasing the number of crops in a rotation system) did not result in as much SOC increase on average as did a change from conventional to zero tillage, but crop rotation was still more effective in retaining C and N in soil than monoculture. VandenBygaart et al. (2003) reported in their review of Canadian studies that, regardless of tillage treatment, more frequent fallowing resulted in a lower potential to gain SOC in Canada and Wall et al. (2004) reported results from northern Kazakhstan showing that reductions over time in SOC in soils where crops are produced with conservation tillage were related to fallow frequency as the fallow is tilled frequently for weed control. Legume-based cropping systems increased C and N contents in a southern Brasil Acrisol due to the higher residue input in a long-term (17 years) zero tillage cereal and legume-based cropping system (Diekow et al. 2005). Introducing legumes in rotation enhances the N pool by symbiotically fixed N (Jarecki and Lal 2003). On the other hand, Campbell and Zentner (1993) reported that flax (*Linum usitatissimum* L.) contributed smaller amounts of residue with higher lignin contents to the soil than wheat, and flax straw tended to be more easily blown off fields after harvest than wheat straw and therefore had a lesser effect on SOC (or soil N). West and Post (2002) reported that changing from continuous maize to a maize–soyabean rotation did not result in increased SOC. Continuous maize generally produces more residue and C input than a maize–soyabean rotation.

The effect of crop rotation on SOC contents can be due to increased biomass C input, because of the greater total production, or due to the changed quality of the residue input. The mechanism of capturing C in stable and long-term forms might be different for different crop species (Gál et al. 2007). West and Post (2002) reported that while moving from wheat–fallow to continuous wheat may increase C residue inputs, it did not appear to increase SOC as effectively as a continuous cropping system that rotates wheat with other crops. Gregorich et al. (2001) found that SOC below the plough layer was greater in legume-based rotations than under maize in monoculture. They observed that the legume-based rotations contained much greater amounts of aromatic C content (a highly biologically resistant form of carbon) below the plough layer than continuous maize.

7.3.1.1.4 Conservation agriculture: the combined effect of minimum tillage, residue retention and crop rotation on soil organic carbon

Conservation agriculture is not a single component technology but a system that includes the cumulative effect of all its three basic components. The crop intensification component will result in an added effect on SOC in zero tillage systems. West and Post (2002) reported that although relative increases in SOC were small, increases due to the adoption of zero tillage were greater and occurred much faster in continuously-cropped than in fallow-based rotations. Sisti et al. (2004) found that under a continuous sequence of wheat (winter) and soyabean (summer) the concentrations of SOC to 100 cm depth under zero tillage were not significantly different from those under conventional tillage. However, in the rotations with vetch planted as a winter green-manure crop, SOC concentrations were approximately 17 Mg ha^{-1} higher under zero tillage than under conventional tillage. It appears that the contribution of N_2 fixation by the leguminous green manure (vetch) in the cropping system was the principal factor responsible for the observed C accumulation in the soil under zero tillage, and that most accumulated C was derived from crop roots. To obtain an accumulation of SOM there must be not only a C input from crop residues but a net external input of N e.g. including an N-fixing green-manure in the crop rotation (Sisti et al. 2004). Conventional tillage can diminish the effect of an N-fixing green-manure either because the N-input can be reduced by soil mineral N release or the N can be lost by leaching (NO_3^-) or in gaseous forms (via denitrification or NH_3 volatilisation) due to SOM mineralisation stimulated by tillage (Alves et al. 2002). Hence, intensification of cropping practices by the elimination of fallow and moving toward continuous cropping, is the first step toward increased SOC contents. Reducing tillage intensity, by the adoption of zero tillage enhances the cropping intensity effect.

7.3.1.2 Soil organic carbon fractionation

Hermle et al. (2008) distinguished the following soil C fractions: (i) the easily decomposable fraction (labile), representing an early stage in the humification process, (ii) material stabilised by physical–chemical mechanisms (intermediary) and (iii) the biochemically recalcitrant fraction (stable). The different carbon fractions of the soil have different availability and turnover times in the soil. The SOC of the labile pool, which consists mainly of particulate organic matter (POM) and some dissolved organic carbon, is readily available and consequently rapidly decomposed while the resistant SOC fraction is old, in close contact with mineral surfaces, and provides limited access to micro-organisms (Hermle et al. 2008). The labile fraction plays a crucial role in the formation of aggregates (Six et al. 2001), and responds rapidly to changes in soil management because of its rapid turnover time (Franzluebbers and Stuedemann 2002). Therefore, it can be a good indicator of early changes in SOC (Gregorich et al. 1994, Haynes and Beare 1996). Oorts et al. (2007) stated that 58% of the difference in SOC between tillage and zero tillage was due to a difference in total POM (labile fraction). Research generally shows an enrichment of the organic matter in labile forms as tillage intensity reduces (Chan et al. 2002, Angers et al. 1993a, 1993b). However, the Herlme et al. (2008) definition of the labile fraction is not always used by other authors. Some studies use different POM characteristics (e.g. fine, coarse, …), complicating comparisons. However, increases in light fraction C due to zero tillage were greater than those for total C in the results of Larney et al. (1997), supporting the idea that zero tillage favours the accumulation of decomposable C. Alvaro-Fuentes et al. (2008) found higher POM-C levels and mineral-associated C fraction levels at the soil surface (0–5 cm) under zero tillage than under conventional tillage. Zero tillage increased the ratio of fine POM to total soil organic matter by 19 and 37% compared with tillage after 4 and 10 years, respectively (Pikul et al. 2007). After 19 years, Chan et al. (2002) observed that tillage and stubble burning resulted in lower levels of different organic C fractions compared to zero tillage and residue retention, respectively. Tillage preferentially reduced the particulate organic C (>53 µm, both free and associated), whereas stubble burning reduced the incorporated organic C (<53 µm).

Hermle et al. (2008) concluded that the intermediate SOC fraction contributes up to 60% of the total SOC, but soil cover by plant residues under zero tillage favoured the accumulation of labile particulate C as compared to ploughing. Therefore, the observed higher SOC concentration (0–10 cm) for zero tillage compared to conventional tillage was mostly due to more labile organic matter. The importance of crop residue retention to the labile pool has also been reported by Graham et al. (2002): increased input of organic matter due to either increased return of crop residue or increased deposition due to higher yields (induced by fertilizer) caused a proportionally greater increase in labile organic matter than in total soil organic matter. Ha et al. (2008) reported that different residues resulted in different levels of POM, which cultivate distinct microbial communities.

Crop rotation can influence the different C fractions. According to Pikul et al. (2007), systems that used more diverse crop rotations (maize-soyabean, maize-soyabean-spring wheat-alfalfa [*Medicago sativa* L.], maize-soyabean-oat and pea hay [*Pisum sativum* L.]-alfalfa-alfalfa) had greater proportions of fine POM than monoculture (continuous maize). Larney et al. (1997) found that the effects of tillage system on light fraction C were less than those of cropping intensity (fallow frequency). Also Arshad et al. (2004) found an effect of crop rotation and fallow intensity on light fraction C under zero tillage. Light fraction C was greater under continuous wheat than under other crop rotations, but especially greater than under the rotation with fallow. Continuous wheat straw input each year has been shown to improve light fraction C in other studies from western Canada (Liang et al. 2002, Janzen et al. 1998).

7.3.2 Nutrient availability

Tillage, residue management and crop rotation have a significant impact on nutrient distribution and transformation in soils (Galantini et al. 2000, Etana et al. 1999), usually related to the effects of conservation agriculture on SOC contents (*7.3.1. Soil organic carbon*). Similar to the findings on SOC, distribution of nutrients in a soil under zero tillage is different to that in tilled soil. Increased stratification of nutrients is generally observed, with enhanced conservation and availability of nutrients near the soil surface under zero tillage as compared to conventional tillage (e.g. Duiker and Beegle 2006, Franzluebbers and Hons 1996, Follett and Peterson 1988).

The altered nutrient availability under zero tillage compared to conventional tillage may be due to surface placement of crop residues in comparison with incorporation of crop residues with tillage (Ismail et al. 1994, Unger 1991, Blevins et al. 1977). Slower decomposition of surface placed residues (Balota et al. 2004, Kushwaha et al. 2000) may prevent rapid leaching of nutrients through the soil profile, which is more likely when residues are incorporated into the soil. However, the possible development of more continuous pores between the surface and the subsurface under zero tillage (Kay 1990) may lead to more rapid passage of soluble nutrients deeper into the soil profile than when soil is tilled (Franzluebbers and Hons 1996). Furthermore, the response of soil chemical fertility to tillage is site-specific and depends on soil type, cropping systems, climate, fertilizer application and management practices (Rahman et al. 2008).

The density of crop roots is usually greater near the soil surface under zero tillage compared to conventional tillage (Qin et al. 2004). This may be common under zero tillage as in the study of Mackay et al. (1987) a much greater proportion of nutrients was taken up from near the soil surface under zero tillage than under tilled culture, illustrated by a significantly higher P uptake from the 0–7.5 cm soil layer under zero tillage than under conventional tillage. However, research on nutrient uptake by Hulugalle and Entwistle (1997) revealed that nutrient concentrations in plant tissues were not significantly affected by tillage or crop combinations. Although there are reports of straw burning increasing nutrient availability (Du Preez et al. 2001), burning crop residues is not considered sustainable given the well documented negative effects on physical soil quality, especially when it is combined with reduced tillage (Limon-Ortega et al. 2002). Mohamed et al. (2007) observed only short-term effects of burning on N, P and Mg availability. As a consequence of the short-term increased nutrient availability limited nutrient uptake by plants after burning, leaching of N, Ca, K, and Mg increased significantly after burning (Mohamed et al. 2007).

7.3.2.1 Nitrogen availability

The presence of mineral soil N available for plant uptake is dependent on the rate of C mineralization. The literature concerning the impact of reduced tillage with residue retention on N mineralization is inconclusive. Zero tillage is generally associated with a lower N availability because of greater immobilization by the residues left on the soil surface (Bradford and Peterson 2000, Rice and Smith 1984). Some authors suggest that the net immobilization phase when zero tillage is adopted, is transitory, and that in the long run, the higher, but temporary immobilization of N in zero tillage systems reduces the opportunity for leaching and denitrification losses of mineral N (Follet and Schimel 1989, Rice et al. 1986, Lamb et al. 1985). According to Schoenau and Campbell (1996), a greater immobilization in conservation agriculture can enhance the conservation of soil and fertilizer N in the long run, with higher initial N fertilizer requirements decreasing over time because of reduced losses by erosion and the build-up of a larger pool of readily mineralizable organic N.

7.3.2.1.1 Total nitrogen content

Effects of conservation agriculture on total N content generally mirrors those observed for total SOC, as the N cycle is inextricably linked to the C cycle (Bradford and Peterson 2000). Astier et al. (2006) and Govaerts et al. (2007c) observed a significantly higher total N under both zero tillage and permanent raised beds compared to conventional tillage in the highlands of Central Mexico. Similar results were obtained by Borie et al. (2005) and Atreya et al. (2006) in other agro-ecological areas. In contrast, tillage and cropping system did not influence SOC and total N in the work of Sainju et al (2008). Larney et al. (1997) reported that zero tillage had a greater effect on mineralizable N and light fraction N than on total N. Significant increases in total N have been measured with increasing additions of crop residue (Graham et al. 2002). Similarly, increasing the amount of straw retained under permanent raised beds increased total N significantly (Govaerts et al. 2007c).

7.3.2.1.2 The influence of tillage practice on nitrogen mineralization

Tillage increases aggregate disruption, making organic matter more accessible to soil microorganisms (Six et al. 2002, Beare et al. 1994) and increasing mineral N release from active and physically protected N pools (Kristensen et al. 2000). Lichter et al. (2008) reported that permanent raised beds with residue retention resulted in more stable macroaggregates and increased protection of C and N in the microaggregates within the macroaggregates compared to conventionally tilled raised beds. This increases susceptibility to leaching or denitrification if no growing crop is able to take advantage of these nutrients at the time of their release (Randall and Iragavarapu 1995, Christensen et al. 1994, Doran 1980). Randall and Iragavarapu (1995) reported about 5% higher NO_3-N losses with conventional tillage compared to zero tillage. Jowkin and Schoenau (1998) report that N availability was not greatly affected in the initial years after switching to zero tillage in the brown soil zone in Canada. Other authors reported that N-mineralization rate increased as tillage decreased: Larney et al. (1997) reported that, after eight years of the tillage treatments, the content of N available for mineralization was greater in zero-tilled soils than in conventionally tilled soil under continuous spring wheat. Wienhold and Halvorson (1999) found that nitrogen mineralization generally increased in the 0-5 cm soil layer, as the intensity of tillage decreased. Govaerts et al. (2006c) found after 26 cropping seasons in a high-yielding, high-input irrigated production system that the N mineralization rate was higher in permanent raised beds with residue retention than in conventionally tilled raised beds with all residues incorporated, and also that N mineralization rate increased with increasing rate of inorganic N fertilizer application.

The tillage system determines the placement of residues. Conventional tillage implies incorporation of crop residues while residues are left on the soil surface in the case of zero tillage. These differences in the placement of residues contribute to the effect of tillage on N dynamics. Balota et al. (2004) and Kushwaha et al. (2000) reported that incorporated crop residues decompose 1.5 times faster than surface placed residues. However, also the type of residues and the interactions with N management practices determine C and N mineralization (Verachtert et al. 2009).

7.3.2.1.3 The influence of crop residues on nitrogen mineralization

The composition of residues left on the field will affect their decomposition (Trinsoutrot et al. 2000). The C/N ratio is one of the most often used criteria for residue quality (Hadas et al. 2004, Nicolardot et al. 2001, Vanlauwe et al. 1996), together with initial residue N, lignin, polyphenols and soluble C concentrations (Moretto et al. 2001, Trinsoutrot et al. 2000, Thomas and Asakawa 1993). During the decomposition of organic matter, inorganic N can be immobilized (Zagal and Persson 1994), especially when organic material with a large C/N ratio is added to the soil. Kumar and Goh (2002) found that total soil N mineralization was significantly correlated with the C/N ratio of the residues.

While some plant species commonly used as cover crops (e.g. *Tithonia diversifolia*) have relatively high N and P contents, crop residues have very low N (ca. 1%) and P contents (ca. 0.1%) (Palm et al. 2001a). Given crop residues lignin and polyphenol contents (Palm et al., 2001b), these residues play a more important role contributing to SOM build-up than as inorganic nutrient sources for plant growth (Palm et al. 2001a, Delve et al. 2000). However, nitrogen immobilization can occur as a consequence of cereal residue retention, particularly during first years of implementation (Erenstein 2002). Kandeler et al. (1999) reported that after a 4-year period, N mineralization in a conventionally tilled treatment was significantly higher than that in minimum and reduced tillage plots due to buried organic materials. However, Govaerts et al. (2006c) reported that in soil with retention of maize residues, N immobilization still occurred after 13 years in an irrigated maize-wheat rotation system in the northwest of Mexico.

7.3.2.2 Phosphorus

Numerous studies have reported higher extractable P levels in zero tillage than in tilled soil (e.g. Duiker and Beegle 2006, Du Preez et al. 2001, Franzluebbers and Hons 1996, Edwards et al. 1992, Follett and Peterson 1988, Hargrove et al. 1982), largely due to reduced mixing of the fertilizer P with the soil, leading to lower P-fixation. This is a benefit when P is a limiting nutrient, but may be a threat when P is an environmental problem because of the possibility of soluble P losses in runoff water

(Duiker and Beegle 2006). After 20 years of zero tillage, extractable P was 42% greater at 0-5 cm, but 8-18% lower at 5-30 cm depth compared with conventional tillage in a silt loam (Ismail et al. 1994). Also Unger (1991) and Matowo et al (1999) found higher extractable P levels in zero tillage compared to tilled soil in the topsoil. Accumulation of P at the surface of continuous zero tillage is commonly observed (e.g. Franzluebbers and Hons 1996, Edwards et al. 1992, Follett and Peterson 1988, Eckert and Johnson 1985, Hargrove et al. 1982). Concentrations of P were higher in the surface layers of all tillage systems as compared to deeper layers, but most strikingly in zero tillage (Duiker and Beegle 2006). When fertilizer P is applied on the soil surface, a part of P will be directly fixed by soil particles. When P is banded as a starter application below the soil surface, authors ascribed P stratification partly to recycled P by plants (Duiker and Beegle 2006, Eckert and Johnson 1985). Duiker and Beegle (2006) suggest there may be less need for P starter fertilizer in long-term zero tillage due to high available P levels in the topsoil where the seed is placed. Deeper placement of P in zero tillage may be profitable if the surface soil dries out frequently during the growing season as suggested by Mackay et al. (1987). In that case, injected P may be more available to the crop. However, if mulch is present on the soil surface in zero tillage the surface soil is likely to be moister than conventionally tilled soils and there will probably be no need for deep P placement, especially in humid areas. Franzluebbers et al. (1995, 1994) suggested that the redistribution of extractable P in zero tillage compared with conventional tillage is probably a direct result of surface placement of crop residues that leads to accumulation of SOM and microbial biomass near the surface. However Franzluebbers and Hons (1996) and Sidiras and Pavan (1985) also observed higher extractable P levels below the tillage zone, probably due to the accumulation of P in senescent roots and the higher SOC content of the soil. Roldan et al (2007) reported that available P was not affected by tillage system, soil depth or type of crop.

7.3.2.3 Potassium, calcium and magnesium content

Zero tillage conserves and increases availability of nutrients, such as K, near the soil surface where crop roots proliferate (Franzluebbers and Hons 1996). According to Govaerts et al. (2007c), permanent raised beds had a concentration of K 1.65 times and 1.43 times higher in the 0-5 cm and 5-20 cm layer, respectively, than conventionally tilled raised beds, both with crop residue retention. In both tillage systems, K accumulated in the 0-5 cm layer, but this was more accentuated in permanent than in conventionally tilled raised beds. Other studies have found higher extractable K levels at the soil surface as tillage intensity decreases (Ismail et al. 1994, Unger 1991, Lal et al. 1990). Du Preez et al. (2001) observed increased levels of K in zero tillage compared to conventional tillage, but this effect declined with depth. Some authors have observed surface accumulation of available K irrespective of tillage practice (Duiker and Beegle 2006, Matowo et al. 1999, Hulugalle and Entwistle 1997). Follett and Peterson (1988) observed either higher or similar extractable K levels in zero tillage compared to mouldboard tillage, while Roldan et al. (2007) found no effect of tillage or depth on available K concentrations.

Standley et al. (1990) also observed higher exchangeable K in the topsoil (0-2 cm) when sorghum stubble was retained than when the stubble was removed. Govaerts et al. (2007c) found that the K concentration in both the 0-5 cm and 5-20 cm soil layers increased significantly with increasing residue retention on permanent raised beds. This effect was more pronounced for wheat than for maize. It is well known that large amounts of K are taken up by wheat, but most of this remains in the residues after harvest (Du Preez and Bennie 1991). Duiker and Beegle (2006) reported that K accumulated in the rows of the previous crop, probably because it leached from crop residue that accumulated there. Mackay et al. (1987) also observed concentration of K in the crop rows of the zero tillage treatment but not for mouldboard tillage. No effect of crop on K concentrations was observed by Roldan et al. (2007).

Most research has shown that tillage does not affect extractable Ca and Mg levels (Govaerts et al 2007c, Duiker and Beegle 2006, Du Preez et al. 2001, Hulugalle and Entwistle 1997, Franzluebbers and Hons 1996, Hargrove et al. 1982) especially where the CEC is primarily associated with clay particles (Duiker and Beegle 2006). Edwards et al. (1992), however, observed higher extractable Ca concentrations with zero tillage than with conventional tillage on an Ultisol, which they attributed to the higher SOM content under zero tillage. The same conclusion was reached by Sidiras and Pavan

(1985) who found increased available Ca and Mg concentrations to 60 cm depth in both an oxisol and alfisol in Brazil. In contrast, Blevins et al (1983) reported lower extractable Ca under zero tillage than conventional tillage.

Also the vertical Ca and Mg stratification seems unaffected by tillage or crop according to some authors (Govaerts et al 2007c, Du Preez et al. 2001, Franzluebbers and Hons 1996), while others reported different vertical Ca and/or Mg stratification between tillage practices (Duiker and Beegle 2006, Hulugalle and Entwistle 1997, Edwards et al. 1992, Blevins et al. 1983, 1977, Hargrove et al. 1982). The Ca concentrations were higher in the 0–5 cm layer of zero tillage than in the deeper layers in the work of Duiker and Beegle (2006) but the reverse was true for mouldboard tillage. This could be attributable to the tillage after the last lime application (calcitic limestone) in the mouldboard treatment. Higher concentrations of Mg were observed in the surface soil of zero tillage plots than in those with mouldboard or conventional tillage (Edwards et al. 1992, Blevins et al. 1983, Hargrove et al. 1982), possibly as a result of application of Mg-containing dolomitic limestone to correct pH.

7.3.2.4 Cation exchange capacity

The high organic matter contents at the soil surface, commonly observed under conservation agriculture (*7.3.1.1 Total soil organic carbon content*), can increase the CEC of the topsoil (Duiker and Beegle 2006). However, the average CEC in the 0–15 cm layer was not significantly different between tillage systems in the same study. This was confirmed by Govaerts et al. (2007c), who did not find an effect of tillage practices and crop on CEC. The retention of crop residues, however, significantly increased the CEC in the 0–5 cm layer of permanent raised beds compared to soil from which the residues were removed, but there was no difference in the 5–20 cm layer (Govaerts et al. 2007c).

7.3.2.5 Micronutrient cations and aluminium

Increasing supply to food crops of essential micronutrients might result in significant increases in their concentrations in edible plant products, contributing to consumers' health (Welch 2002). Micronutrient cations (Zn, Fe, Cu and Mn) tend to be present in higher levels under zero tillage with residue retentions compared to conventional tillage, especially extractable Zn and Mn near the soil surface due to surface placement of crop residues (Franzluebbers and Hons 1996). In contrast, Govaerts et al. (2007c) reported that tillage practice had no significant effect on the concentration of extractable Fe, Mn and Cu, but that the concentration of extractable Zn was significantly higher in the 0-5 cm layer of permanent raised beds compared to conventionally tilled raised beds with full residue retention. Similar results were reported by Du Preez et al (2001) and Franzluebbers and Hons (1996). Residue retention significantly decreased concentrations of extractable Mn in the 0-5 cm layer in permanent raised beds (Govaerts et al. 2007c). According to Peng et al. (2008), however, Mn concentrations are increased by higher SOM contents.

Caires et al (2008) investigated Al toxicity in Brazilian acidic soils under zero tillage with black oat (*Avena strigosa* Schreb.) residue retention and found that aluminium toxicity is low in zero tillage systems during cropping seasons that have adequate and well-distributed rainfall. The authors suggest that the decrease in aluminium toxicity to crops grown under zero tillage may be associated with the formation of Al-organic complexes when water in the topsoil is available.

7.3.3 Acidity

In numerous studies, the pH of the topsoil was found to be lower for zero tillage than for conventional tillage (Franzluebbers and Hons 1996, Dick 1983, Blevins et al. 1983, 1977, Hargrove et al. 1982). Most differences in pH were only found in the topsoil (0-5 cm), although some authors observed a decline in soil pH under zero tillage to a greater depth. Roldan et al. (2007) found a significant acidification under zero tillage in the 0-5 cm and 5-15 cm depths. After nine years of zero tillage, the pH was lower in than in conventional tillage to the depth of 60 cm (Hulugalle and Entwistle 1997). However, Sidiras and Pavan (1985) found less acidification (and therefore higher pH) under zero tillage than under conventional tillage to a depth of 60 cm in both an oxisol and an alfisol in Paraná, Brazil.

According to Franzluebbers and Hons (1996), the greater SOM accumulation in the topsoil with zero tillage led to acidity from decomposition. In contrast, Duiker and Beegle (2006) suggested that the pH under zero tillage was buffered because of the higher SOM content. It has also been proposed that greater leaching under zero tillage was responsible for the higher removal of bases, which led to a lowering of pH (Blevins et al. 1977), but some experiments report a higher susceptibility for leaching when tillage increases (Christensen et al. 1994). Others suggested the lower topsoil pH could be due to the acidifying effect of nitrogen and phosphorus fertilizers applied more superficially under zero tillage than under conventional tillage (Duiker and Beegle 2006, Prasad and Power 1991). Based on this assumption, the opposite pH trend found by Du Preez et al. (2001) was attributed to the fact that nitrogen fertilizers were banded to the same depth in zero and conventional tillage. Also Govaerts et al. (2007c) observed a significantly higher pH in the topsoil of the permanent raised beds with full residue retention compared to conventional raised beds with residue retention. No such effect was found in the 5–20 cm layer. In Scandinavian soils, however, the soil pH was normally unaffected by tillage systems and depths (Rasmussen 1999). Duiker and Beegle (2006) did not observe significant tillage effects on the average pH of the 0-15 cm layer, but the surface pH was higher under zero tillage than with mouldboard tillage, probably due to liming methodology. Because more lime would have been present at the surface of soil under zero tillage, the pH was depressed less compared to mouldboard tillage where lime was incorporated into the plough layer.

7.3.4 Salinity/sodicity

According to Govaerts et al. (2007c), permanent raised bed planting is a technology that reduces soil sodicity under rain fed conditions. They found the Na concentration to be 2.64 and 1.80 times lower in 0-5 cm and 5-20 cm layer, respectively, in permanent raised beds compared to conventionally tilled raised beds. Furthermore, the Na concentration increased with decreasing amounts of residue retained on the permanent raised beds. None of the management practices in the rainfed experiment resulted in Na concentrations that dramatically affected soil dispersion. However, the decrease in Na concentration in soil under permanent raised beds with partial or full residue retention compared to conventionally tilled raised beds can be important for saline areas (Sayre et al. 2005). Compared to conventional tillage, values of exchangeable Na, exchangeable sodium percentage and dispersion index were lower in an irrigated Vertisol after nine years of minimum tillage (Hulugalle and Entwistle 1997).

In contrast, Wilson et al. (2000) suggest that tillage tends to reduce the potential for salt accumulation in the root zone of a silt loam soil cropped to paddy rice: greater salt accumulation was observed near the soil surface during the seedling rice growth stage under zero tillage compared to conventional tillage. Roldan et al (2007) observed a lower soil electrical conductivity with mouldboard tillage than with zero tillage on Vertisols in Northern Mexico. Furthermore, a significant interaction was observed between soil tillage and soil depth. In the 5–15 cm layer, there were no differences in soil electrical conductivity between tillage systems or crops. In some cases, Na concentrations were not significantly influenced by tillage practices (Du Preez et al. 2001, Franzluebbers and Hons 1996). Extractable Na increased with depth irrespective of tillage practices and was otherwise little affected by tillage (Franzluebbers and Hons 1996).

7.4 INFLUENCE OF CONSERVATION AGRICULTURE ON BIOLOGICAL SOIL QUALITY

Changes in tillage, residue, and rotation practices induce major shifts in the number and composition of soil fauna and flora, including both pests and beneficial organisms (Bockus and Shroyer 1998, Andersen 1999). Soil organisms respond to tillage-induced changes in the soil physical/chemical environment and they, in turn, have an impact on soil physical/chemical conditions, i.e. soil structure, nutrient cycling, and organic matter decomposition. Interactions among different organisms can have either beneficial or harmful effects on crops (Kladivko 2001).

Bacteria, fungi, and green algae are included in the microflora. The remaining groups of interest are usually referred to as soil fauna. For the purposes of this paper, the system of Lavelle (1997) as described by Kladivko (2001) for discussion of soil fauna will be adopted. Three groups are distinguished, based on their size and their adaptation to living in either the water-filled pore space or the air-filled pore space of soil and litter. The microfauna are small (less than 0.2 mm body width on average), live in the water-filled pore space, and are comprised mainly of protozoa and nematodes. The mesofauna include microarthropods (mainly mites (acarids) and springtails (collembolans)) and the small Oligochaeta, the enchytraeidae. They have an average size of 0.2–2 mm and live in air-filled pore space of soil and litter. The macrofauna are larger than 2 mm and include termites, earthworms, and large arthropods. They have the ability to dig the soil and are sometimes called ‘ecosystem engineers’ because of their large impact on soil structure.

7.4.1 Soil microfauna and -flora

Maintaining soil microbial biomass (SMB) and micro-flora activity and diversity is fundamental for sustainable agricultural management (Insam 2001). Soil management influences soil microorganisms and soil microbial processes through changes in the quantity and quality of plant residues entering the soil, their seasonal and spatial distribution, the ratio between above- and below-ground inputs, and changes in nutrient inputs (Christensen et al. 1994 Kandeler et al. 1999).

7.4.1.1 Microbial biomass

The SMB reflects the soil’s ability to store and cycle nutrients (C, N, P and S) and organic matter, and has a high turnover rate relative to the total soil organic matter (Dick 1992, Carter et al. 1999). Due to its dynamic character, SMB responds to changes in soil management often before effects are measured in terms of organic C and N (Powlson and Jenkinson 1981). The SMB plays an important role in physical stabilization of aggregates (Franzluebbers et al. 1999, Doran et al. 1998). General soil borne disease suppression is also related to total SMB, which competes with pathogens for resources or causes inhibition through more direct forms of antagonism (Weller et al. 2002).

The rate of organic C input from plant biomass is generally considered the dominant factor controlling the amount of SMB in soil (Campbell et al. 1997). Franzluebbers et al. (1999) showed that as the total organic C pool expands or contracts due to changes in C inputs to the soil, the microbial pool also expands or contracts. A continuous, uniform supply of C from crop residues serves as an energy source for microorganisms. In the subtropical highlands of Mexico residue retention resulted in significantly higher amounts of SMB-C and N in the 0-15 cm layer compared to residue removal (Govaerts et al. 2007b). Spedding et al. (2004) found that residue management had more influence than tillage system on microbial characteristics, and higher SMB-C and N levels were found in plots with residue retention than with residue removal, although the differences were significant only in the 0-10 cm layer.

The influence of tillage practice on SMB-C and N seems to be mainly confined to the surface layers, with a stronger stratification when tillage is reduced (Alvear et al. 2005, Salinas-Garcia et al. 2002). Alvear et al. (2005) found higher SMB-C and N in the 0-20 cm layer under zero tillage than under conventional tillage (disk-harrowing to 20 cm) in an Ultisol from southern Chile and attributed this to the higher levels of C substrates available for microorganism growth, better soil physical conditions and higher water retention under zero tillage. Pankhurst et al. (2002) found that zero tillage with direct seeding into crop residue increased the build-up of organic C and SMB in the surface soil. Salinas-Garcia et al. (2002) reported that SMB-C and N were significantly affected by tillage, but primarily at the soil surface (0–5 cm) where they were 25–50% greater with zero tillage and minimum tillage than with disk ploughing to 30 cm. At lower depths (5-10 and 10-15 cm), SMB-C and N were generally not significantly different. The favourable effects of zero tillage and residue retention on soil microbial populations are mainly due to increased soil aeration, cooler and wetter conditions, lower temperature and moisture fluctuations, and higher carbon content in surface soil (Doran, 1980).

Bell et al. (2006) examined the effects of several rotations under dryland conditions on Vertisols in cotton-based systems in Australia, and concluded that microbial activity was related to the length of the fallow rather than to the rotation per se, and that it was restricted to the surface layers. Their results were confirmed in the research of Acosta-Martinez et al. (2007), who found that reducing fallow increased SMB-C and N in wheat-fallow systems in Colorado, but only at the 0-5 cm depth. Govaerts et al. (2007b) found a significant increase in SMB-C and N with crop rotation when residues were retained under zero tillage in the highlands of Mexico. Monoculture of maize with residue retention resulted in increased SMB with zero tillage compared to conventional tillage, but no significant differences in SMB were found between the same tillage systems with a maize-wheat rotation and crop residue retention. Each tillage operation increases organic matter decomposition with a subsequent decrease in SOM (Buchanan and King 1992). However, wheat in the rotation tends to buffer against soil C depletion (Govaerts et al. 2007b).

7.4.1.2 Functional diversity

Functional diversity and redundancy, which refers to a reserve pool of quiescent organisms or a community with vast interspecific overlaps and trait plasticity, are signs of increased soil health, and allow an ecosystem to maintain a stable soil function (Wang and McSorley 2005). Soil microbial biomass methods provide only limited information on the functional diversity of the microbial community (White et al. 2005). It is not possible to determine the functional diversity of soil microbial communities based on community structure, largely because microorganisms are often present in soil in resting or dormant stages, during which they are not functionally active (White and MacNaughton 1997). It is, therefore, generally believed that direct measurement of the functional diversity of soil microbial communities is likely to provide additional information on the functioning of soils (Garland and Mills 1991, Giller et al. 1997) e.g. by examining the number of different C substrates used by the culturable microbial community.

Lupwayi et al. (1998, 1999) reported a larger functional diversity under zero tillage with residue retention than under conventional tillage in the Peace River region of Canada. Lupwayi et al. (2001) found that conventional tillage significantly reduced microbial diversity in an acidic and C-poor Luvisolic soil, but detected no significant effects on near-neutral, C-rich Luvisolic and Chernozemic soils. This underlines the importance of soil C in maintaining a healthy soil (Lupwayi et al. 2001). This was confirmed by the research of Govaerts et al. (2007b) on a Phaeozem soil relatively rich in C, where differences in the community-level physiological profile of the SMB between zero and conventional tillage were minimal as long as residues were maintained, while functional diversity was decreased in zero tillage with residue removal. Kandeler et al. (1999) reported that on a Chernozem a trend towards a significant increase in functional diversity caused by reduced tillage became clear within the first year of the experiment, and this effect was still evident after eight years.

Plant roots play an important role in shaping soil microbial communities by releasing a wide range of compounds that may differ between plants (Salles et al. 2004). This variation is known to select divergent bacterial communities (Lupwayi et al. 1998, Wieland et al. 2001). Garland (1996) found distinctive patterns of C source utilization for rhizosphere communities of wheat, white potato, soyabean and sweetpotato and Govaerts et al. (2007b) reported differences in the community level physiological profile between soils under maize compared to soils under a wheat crop. This indicates the importance of crop rotation for soil health, but more research is needed to identify the underlying processes and take advantage of them when implementing crop rotations.

7.4.1.3 Enzyme activity

Soil enzymes play an essential role in catalyzing the reactions necessary for organic matter decomposition and nutrient cycling. They are involved in energy transfer, environmental quality and crop productivity (Dick 1994, Tabatabai 1994). Management practices such as tillage, crop rotation and residue management may have diverse effects on various soil enzymes (Tabatabai 1994) and in this way may alter the availability of plant nutrients. Enzymatic activities generally decrease with soil depth (Green et al. 2007, Curci et al. 1997, Dick et al. 1988). Zero tillage management increases stratification of enzyme activities in the soil profile, probably because of similar vertical distribution of organic residues and microbial activity (Green et al. 2007). Consequently, differentiation among management practices is greater in the surface soil (Green et al. 2007, Alvear et al. 2005). Zero tillage in a volcanic soil in Chile increased dehydrogenase, acid phosphomonoesterase and urease activities mainly in the 0-5 cm layer compared with a soil disk-harrowed to 20 cm (Alvear et al. 2005). Roldán et al. (2007) found higher dehydrogenase and phosphatase activities in the 0-5 cm layer with zero tillage than with mouldboard ploughing to 20 cm on a Vertisol, but no difference was found below 5 cm. Even with greater acid phosphatase, β-glucosidase, and arylamidase enzyme activities in the surface layer (0-5 cm) under zero tillage, Green et al. (2007) did not observe significant differences among tillage practices for any of the enzyme activities on a soil profile basis (0–30 cm) in an Oxisol in the Cerrado region of Brazil. This suggests that tillage mainly changes the vertical distribution of enzyme activity within the profile.

Crop rotation and residue management can affect soil enzyme activity. Angers et al. (1993) reported 15% larger alkaline phosphatase activity in a barley-red clover rotation than in continuous barley on a clay soil in Quebec. Reducing fallow in a fallow-wheat rotation encouraged higher enzyme activities of C and P cycling (Acosta-Martinez et al. 2007). The effect of long-term residue burning in a tallgrass prairie ecosystem varied between enzymes: activities of urease and acid phosphatase increased, whereas activities of β-glucosidase, deaminase and alkaline phosphatase decreased (Ajwa et al. 1999).

7.4.1.4 Microbial community structure

Actinomycetes and other bacteria, fungi, protozoa and algae are the most abundant and most metabolically active populations in the soil. Many soil-borne Actinomycetes species produce bioactive metabolites that can be used to produce antibiotics and synthesize cellulase or lignine-degrading enzymes, which makes them an important factor in the decomposition of plant material (Wellington and Toth 1994, McCarthy 1987). Fungi are food for nematodes, mites, and other, larger, soil organisms; but may also attack other soil organisms (Van Elsas et al. 1997). Filamentous fungi are responsible for the decomposition of organic matter (e.g., lignine degradation) and participate in nutrient cycling (both above and below ground litter) (Van Elsas et al. 1997, Parkinson 1994). Of special relevance in agricultural management systems are the arbuscular mycorrhizal fungi, which are ubiquitous symbionts of the majority of higher plants, including most crops. The external mycelium of arbuscular mycorrhizal fungi acts as an extension of host plant roots and absorbs nutrients from the soil, especially those with low mobility such as P, Cu and Zn (Burkert and Robson 1994, Li et al. 1991). Arbuscular mycorrhizae interact with pathogens and other rhizosphere inhabitants affecting plant health and nutrition. Extraradical hyphae are also very important in soil conservation as they are one of the major factors involved in soil aggregation (Roldán et al. 2007). The improvement in aggregate stability is due to a physical effect of a network around soil particles, together with the hyphal production of significant amounts of an insoluble glycoprotein named glomalin, which cements soil components (Wright and Anderson 2000, Wright et al. 1999).

When crop residues are retained, they serve as a continuous energy source for microorganisms. Retaining crop residues on the surface also increases microbial abundance, because microbes encounter improved conditions for reproduction in the mulch cover (Salinas-Garcia et al. 2002, Carter and Mele 1992). Crop residue retention resulted in increased populations of Actinomycetes, total bacteria, and fluorescent *Pseudomonas*, under both zero and conventional tillage in the highlands of Mexico (Govaerts et al. 2008a). Höflich et al. (1999) studied rhizosphere bacteria in sandy loam and loamy sand soils. Reducing tillage depth from 30 to 15 cm stimulated rhizosphere bacteria in different soil layers, particularly *Agrobacterium* spp. and *Pseudomonas* spp. in winter wheat, winter barley, winter rye, and maize. The study of Govaerts et al. (2008a) indicated a clear interaction between tillage and residue management on micro-flora populations. Zero tillage per se is not responsible for the increased micro-flora, but rather it is the combination of zero tillage and residue retention.

The crop residues at the soil surface under zero tillage tend to be fungal-dominated (Hendrix et al. 1986). Arbuscular mycorrhizal spore number, active hyphal length and glomalin concentration are higher in the topsoil (0-10 cm) under zero tillage than under mouldboard ploughing (Borie et al., 2006). Roldán et al. (2007) also found higher levels of mycorrhizal propagules and glomalin related soil protein under zero tillage than under mouldboard ploughing at a depth of 0–5 cm, but at 5–15 cm depth, differences between tillage systems and crop types were minimal. A generalization often made is that, at the micro-foodweb scale, zero tillage systems tend to be fungal-dominated whereas conventional tillage systems tend to be bacterial-dominated, although this could depend on whether measurements are made near the soil surface or deeper in the soil profile (Kladivko 2001).

Disruption of the network of mycorrhizal hyphae, an important inoculum source when roots senesce, is a proposed mechanism by which conventional tillage reduces root colonization by arbuscular mycorrhiza. Moreover, tillage transports hyphae and colonized root fragments to the upper soil layer, decreasing and diluting their activity as viable propagules for the succeeding crop in rotation (Borie et al. 2006). Simmons and Coleman (2008) attribute the difference in fungal population between zero and conventional tillage systems to the ability of an ecosystem to withstand disturbance, where bacterial-dominated systems are more resilient than fungal dominated systems due to the different energy pathway (Bardgett and Cook 1998, Allen-Morley and Coleman 1989). Moore et al. (2003) postulate that recovery times from disturbance of each energy channel may be different, and result in an alteration of the food web. Soils in zero tillage systems would evolve fungal dominated, ‘slow’ energy channels, while soils in conventional tillage would break down substrate via a bacterial dominated, or ‘fast’ energy channel (de Ruiter et al. 1998, Allen-Morley and Coleman 1989, Hendrix et al. 1986, Coleman et al. 1983). Bell et al (2006) found a predominance of fungal feeding nematodes in the 0–5 cm layer in zero tillage, indicating that decomposition processes were occurring predominantly through the slower, fungal-based channel instead of the bacterial-based energy channel. The nematode population indicated a better balance between fungi and bacteria at the same depth under conventional tillage. No significant differences between tillage systems were found in the 5–15 cm layer. Acosta-Martinez et al. 2007 reported that reducing fallow in a fallow-wheat rotation resulted in greater fungal populations in the 0-5 cm layer.

Yeates and Hughes (1990) found a significantly greater population of nematodes in reduced than in conventional tillage. Rahman et al. (2007) investigated the population abundance of free-living and plant-parasitic nematodes in the 0-10 cm layer in a long-term rotation/tillage/residue management experiment in New South Wales, Australia. Their results showed that residue retention contributed to high population density of free-living (beneficial) nematodes while conventional cultivation, irrespective of residue management, contributed to suppressing plant-parasitic nematodes. In correspondence with Bell et al. (2006), the population of bacteria-feeders (Rhabditidae) was significantly higher in conventional tillage than the zero tillage under residue retention. Accelerated decomposition of stubble with consequent release of nutrients (Blevins et al. 1984), translocation of nutrients in the topsoil, changes in soil structure and physical properties could be contributory factors for greater abundance of nematodes in topsoil in tilled plots (Rahman et al. 2007). In addition, members of Rhabditidae are colonisers that rapidly increase in number under favourable conditions and are tolerant to disturbance (Bongers 1990). Zero tillage with residue burnt had significantly higher populations of Dorylaimidae (omnivores, excluding plant-parasites and predators) than conventional tillage with the same residue management (Rahman et al. 2007). Total freeliving nematode densities (Rhabditidae and Dorylaimidae) were significantly greater in wheat–lupin rotation than the wheat–wheat rotation irrespective of tillage and stubble management practices. In contrast, a greater population of plant-parasitic nematodes was recorded from plots with wheat–wheat than the wheat–lupin rotation (Rahman et al. 2007).

7.4.1.5 Soil borne diseases

A reduction in tillage influences different pest species in different ways, depending on their survival strategies and life cycles (Andersen 1999, Bockus and Shroyer 1998). Species that spend one or more stages of their life cycle in the soil are most directly affected by tillage. A review of 45 studies (Stinner and House 1990) indicated that populations of 28% of pest species increased with decreasing tillage, 29% showed no significant change, and 43% decreased with decreasing tillage. When reduced tillage is combined with residue retained on the soil surface, this provides residue-borne pathogens and beneficial species with substrates for growth, and pathogens are at the soil surface, where spore release may occur. Many plant pathogens use the residue of their host crop as a food base and as a 'springboard' to infect the next crop. This includes a diversity of necrotrophic leaf-, stem-, and inflorescence-attacking fungal pathogens that survive as reproductive and spore-dissemination structures formed within the dead tissues of their hosts. These structures are thereby ideally positioned on the soil surface and beneath the canopy of the next crop in zero tillage cropping systems (Cook 2006).

The most common root rot pathogens found on cereals under zero tillage systems (Paulitz et al. 2002, Bockus and Shroyer 1998) are: take-all, caused by *Gaeumannomyces graminis* (Sacc.) Arx & Olivier var. *tritici* I Walker; Rhizoctonia root rot and bare patch caused by *Rhizoctonia solani* Kühn AG 8; Pythium damping-off and root rot caused by *Pythium aphanidermatum* (Edison) Fitzp and other species of the same genus; Fusarium crown, foot and root rot caused by *Fusarium culmorum* (W.G. Sm.) Sacc; *F. pseudograminearum* O'Donnell et T. Aoki and other species belonging to the genus *Fusarium* (Paulitz et al. 2002); common root rot caused by *Bipolaris sorokiniana* (Sacc.) Shoem. (Mathre et al. 2003, Wildermuth et al. 1997). The host range of take-all is limited to wheat, barley, and closely related cool season grasses, which is still a wide host range compared with pathogens that specialize not just in plant species but also in plant genotypes within the species (Cook 2006). *Rhizoctonia* causes lesions and pruning of seminal and crown roots in cereals. In its acute phase, this disease results in patches of killed or stunted plants several meters in diameter, and crop yields are drastically reduced (Pumphrey et al. 1987). *Rhizoctonia solani* AG-8 survives best in living host root tissue, which includes roots of volunteers and grassy weeds (Paulitz et al. 2002). *Pythium* species are among the most common soil-borne pathogens of plants worldwide and are ubiquitous inhabitants of the top 8–10 cm of virtually all soils, obtaining their nutrients though a combination of parasitic and saprophytic activities. Although best known for their ability to indiscriminately cause seed decay and damping off of seedlings, these oomycetes are equally or more important for their ability to destroy the plant's fine rootlets so critical for uptake of relatively immobile mineral nutrients such as phosphorus (Cook 2006, Paulitz et al. 2002). *Fusarium* spp. are a diverse group of fungi that damage small-grain cereals by rotting the seed, seedlings, roots, crowns, basal stems, or heads (spikes). These same species also infect maize, grasses, and some broadleaf crops. Foot-rot fungi are considered 'unspecialized' pathogens because they can attack any plant tissue if conditions at the tissue surface are favourable for infection. These pathogens also have ecological differences that influence their survival and pathogenicity (Paulitz et al. 2002).

Many studies have examined the impact of root rot diseases on wheat and barley grown with tillage, but few have focused on the effects of conservation agriculture, and those that have done so have yielded conflicting conclusions (Schroeder and Paulitz 2006). Cook (2006) stated that the potential for root infection by take-all, *Pythium* root rot and *Rhizoctonia* root rot is enhanced with zero tillage because of the cooler and wetter surface soil (where these pathogens reside) that prevails when residues of the previous wheat crop is left on the soil surface, compared to when the residue is buried. Cold soil at the depth of seeding is stressful to plants during seedling emergence. In the case of wheat, the low-temperature stress predisposes the plants to greater pressure from root disease (Cook 1992, Cook et al. 1987). However, this potential does not always result in clear effects. In Saskatchewan, the incidence of take-all was lower in zero tillage compared to conventionally tilled plots (Bailey et al. 1992, 2001). In contrast, Moore and Cook (1984) demonstrated that take-all was more severe with zero tillage than when planting was done into a prepared seedbed. Ramsey (2001) examined tillage effects on take-all in a 3-year survey of 270 wheat fields in eastern Washington and found no difference in the amount of take-all between conventional and zero tillage, in either high- or low-rainfall areas. Also Schroeder and Paulitz (2006) found take-all and *Pythium* root rot having little if any effect when fields were converted from conventional to zero tillage. In a study in Australia, the incidence of take-all increased with direct seeding in two experiments, but not in a third (Roget et al. 1996). Infected plant residues left undisturbed in the soil can present a higher risk for infection of the next crop than if this tissue is fragmented into smaller pieces with tillage. On the other hand, tilling the soil will also distribute the infested crop residue more uniformly so that more roots of the next crop will be exposed more uniformly to infection Paulitz et al. (2002).

Data suggest that consistently higher levels of *Rhizoctonia* root rot of wheat are associated with zero tillage (Roget et al. 1996, Smiley et al. 1996, Pumphrey et al. 1987, Rovira 1986, Weller et al. 1986, MacNish et al. 1985). More *Rhizoctonia* root rot also was observed for direct-seeded barley (Smiley and Wilkins 1993). Schroeder and Paulitz (2006) found that *Rhizoctonia* root rot and yield did not differ between tillage types during the first 2 years. However, in the third and fourth years of the transition to direct seeding, a higher incidence of *Rhizoctonia* root rot, increased hyphal activity of *R. solani*, and reduced yields were observed in plots without tillage. In contrast, in a more recent study conducted in Washington, the severity of *Rhizoctonia* did not differ between conventionally tilled and direct-seeded plots following several years of direct seeding (Schillinger et al. 1999).

Higher population densities of *Pythium* spp. were detected in plots with zero tillage compared with tilled plots (Pankhurst et al. 1995, Cook et al. 1990). This is thought to result from the favourable effects of low temperature and high soil moisture on *Pythium* activity and possibly also from the stimulatory effects of fresh wheat straw on *Pythium* as a saprophyte in soil. As saprophytes, they are the first to colonize fresh plant material added to soil, such as ploughed down green manure and bright unweathered wheat straw, plant materials not already fully occupied by other microbial inhabitants (Cook et al. 1990). However, Smiley and Wilkins (1993) showed that the incidence of *Pythium* root rot did not differ between zero and conventionally tilled plots.

Since the *Fusarium* foot and root rot pathogen survives in the straw, one could hypothesize that the disease would be more severe in direct-seeded than conventionally seeded fields. In Saskatchewan, higher levels of *Fusarium* were associated with zero tillage, based on a multivariate analysis of seven trial-years (Bailey et al. 2001). This study confirmed a previous report of a higher incidence of *Fusarium* in zero tillage wheat (Bailey 1996). Smiley et al. (1996) found increasing *Fusarium* foot rot incidence with increasing amounts of surface residues. Govaerts et al. (2007a, 2006a) found that in the semi-arid and rainfed subtropical highlands of central Mexico, the incidence of *Fusarium* root rot in maize plots with crop rotation with wheat, full residue retention and zero tillage was moderately increased compared to the conventional practice with tillage. However, there was no direct relation between increased root rot and yield.

Crop rotation may reduce pathogen carry-over on crop residues and in the soil. Yields decline with crop monoculture because exposure of the soil microbiota to the roots of the same crop year after year steadily enriches yield-debilitating populations of soil borne pathogens of that crop (Cook 2006). However, even a 2-year rotation cycle, including a 1-year break, can offer significant relief from these pest pressures because of rotation-induced changes in the composition of the soil biota (Cook 2006, Pankhurst 2005). These changes include a reduction in the populations of root pathogens known to be associated with yield decline (Pankhurst et al. 2003, 1999, Stirling et al. 2001). The introduction of rotation breaks has been shown to be effective in improving sugarcane yields (Garside et al. 1999, Bell et al. 1998) and soil health generally (Pankhurst et al. 2003). For the control of take-all in wheat any 2- or even 1-year break to a non host crop, such as a broadleaf crop or oats, can be effective (Smiley et al. 1994, Asher and Shipton 1981), provided that the annual precipitation is high enough to ensure the rapid decomposition of infested host residue (Paulitz et al. 2002). Crop rotations, however, have to be economically viable in order to be adopted by farmers. Take-all remains unquestionably among the most destructive root diseases of wheat worldwide (Cook 2003), for the simple reason that markets for the rotation crops (other than maize and soyabeans) are relatively small and quickly saturated compared with the global market for wheat (Cook 2006). For some root diseases, like *Pythium* and *Rhizoctonia* with a wide host range, the use of crop rotation to manage root rots must include a plant-free (clean fallow) break to be effective (Paulitz et al. 2002). This can mean expense, but no income, from that field, depending on the duration of the break (Cook 2006, Paulitz et al. 2002). Pests can also adapt to crop rotation (Cook 2006). For example, the selection pressure of a 1-year break from maize provided by a maize–soyabean rotation, formerly sufficient to control the maize root worm, has selected for a biotype of this pest with a life cycle timed to hatch every other year rather than every year; the pest is therefore able to remain dormant during the year of soyabeans but become active in the year of maize (Krysan et al.1994).

Reduced tillage combined with residue retention indirectly defines the species composition of the soil microbial community by improving the retention of soil moisture and modifying the soil temperature (Krupinsky et al. 2002). These modifications to the micro-environment influence the biological activity of beneficial micro-organisms in both the crop canopy and the soil. These beneficial soil organisms include those with a capacity to suppress the growth and activity of yield decreasing pathogens (Pankhurst et al. 2003, 2000, Stirling et al. 2001). The changes in the organic matter content with zero tillage and residue retention can also favour the growth of many other microorganisms in the surface layer of soil (0-10 cm) (Follet and Schimel 1989, Doran 1987, Doran 1980).Therefore, reduced tillage combined with crop residue retention may create an environment that is more antagonistic to pathogens due to competition and antibiosis effects (Kladivko 2001, Cook 1990). Several fungal and bacterial species play a role in the biological control of root pathogens and, in general, in the maintenance of soil health. Fluorescent *Pseudomonas* strains, can suppress soil-borne plant pathogens by a variety of mechanisms. These strains of fluorescent *Pseudomonas* are involved in the biological control of pathogenic bacteria, *Fusarium* spp. (de Boer et al. 1999) and fungal soil-borne pathogens (Smith et al. 2003). Many soil-borne *Actinomycetes* species produce bioactive metabolites that can be used to produce antibiotics (Wellington and Toth 1994, McCarthy 1987). Fungi are also predators of parasites of other soil organisms (Van Elsas et al. 1997). *Fusarium* spp. are widely distributed on plants and in the soil. Some *Fusarium* spp. are well-known plant pathogens, but also in this genus many saprophytic species are active biological control agents (Janvier et al. 2007), which may be used to reduce or prevent plant diseases caused by pathogenic *Fusarium* strains and other pathogens (Fravel et al. 2005). Several researchers have reported that in continuous wheat or wheat-barley systems, take-all increased in severity at first (for the first three, four, or five consecutive crops of wheat), but then declined in severity with continued wheat (or wheat/barley) monoculture. Yields recovered, although not fully to the level achieved with crop rotation (Shipton 1972, Gerlach 1968). This is known as the 'take-all decline' (Cook and Baker 1983) and has been attributed to biological control of take-all by rhizosphere-inhabiting bacteria (rhizobacteria) of the taxon *Pseudomonas fluorescens* with the ability to produce the antibiotic 2-4,diacetylphloroglucinol (Cook 2003, Weller et al. 2002). Suppression of *Rhizoctonia* root rot has also been documented in fields monocropped to wheat for extended periods of time (Roget 1995) or in greenhouse experiments following successive plantings of wheat into soils inoculated with *R. solani* AG-8 (Lucas et al. 1993). Data from an experiment reported by Schroeder and Paulitz (2006) showed that fields managed with zero tillage for a prolonged period of time (greater than 12 years) had reduced levels of *Rhizoctonia* root rot, indicating a reversion back to disease levels present in conventional tillage. A possible explanation for similar levels of *Rhizoctonia* in long-term zero and conventionally tilled soils is a change in the microflora of the soil. Hass and Defago (2005) reported that so-called plant growth promotion by rhizobacteria could well be a plant response to less damage from *Pythium* root rot because of antagonistic effects. Govaerts et al. (2006a) found no direct relation between moderately increased root rot and yield with zero tillage with residue retention in the highlands of Mexico. They concluded that, although root diseases may have affected crop performance, disease affected yield less than other critical plant growth factors such as water availability or micro- and macronutrient status. Zero tillage with rotation and residue retention enhanced water availability, soil structure, and nutrient availability more than conventional tillage and, as a result, also gave high yields. Zero tillage and crop retention increased the diversity of microbial life. In the long term, zero tillage with crop residue retention creates conditions favourable for the development of antagonists and predators, and fosters new ecological stability (Govaerts et al. 2007b, 2008a). Thus, the potential exists for a higher general suppression of pathogens in direct seeded soils with crop residue retention (Schroeder and Paulitz 2006). These findings reinforce the need to consider cropping systems holistically, including agro-ecosystem constraints. Although more detailed knowledge of functional relationships among micro-organisms is required to determine the effects of diversity on ecosystem functioning and stability, it is safer to adopt agricultural practices that preserve and restore microbial functional diversity than practices that destroy it (Lupwayi et al. 1998).

Apart from strategic crop rotations and the increased biological control in conservation agriculture systems, the use of soil fumigation has been proposed as a control measure for situation where soil borne diseases may be a problem (Cook 2006). Soil fumigation with methyl bromide has been used in the State of Washington (USA) as an experimental tool to permit the evaluation of potential yield under continuous (monoculture) direct-seeded wheat and barley sequences (Cook et al. 1987, Cook and Haglund 1991). However, fumigation is economical only for certain high-value horticultural crops, such as strawberries in California and tomatoes in Florida. *Pythium* species are also easily eliminated from soil by fumigation with chloropicrin or methyl bromide, which can account for the well known increased growth response of plants to fumigation of the soil (Cook 1992).

Plant breeding has been highly effective against specialized pathogens, such as rust and mildew fungi, because of the availability of genes within the crop species and related species for resistance to these pathogens (Cook 2006). Future strategic research will have to concentrate on genotype by cropping system interactions. Historically, new varieties have facilitated wider adoption of new management, and changes in management have facilitated wider adoption of new varieties. However, little has been done through genetics and breeding to take full advantage of the higher yield potential in conservation agriculture and to overcome some of the yield limiting factors (Sayre and Govaerts 2009, Cook 2006).

Nematode densities range from 2 x 10^5 individuals m^{-2} in arid soils to more than 3 x 10^7 individuals m^{-2} in humid ecosystems (Barker and Koenning 1998). Yield losses due to nematodes can be expected under conventional cropping systems in sub-optimal irrigation and semi-arid conditions. These trends have been reported for the nematode *Pratylenchus thornei* (Nicol and Ortiz-Monasterio 2004, Orion et al. 1984), particularly in dryland situations under moisture-restricted conditions (Bailey et al. 1989, Cook 1981, Piening et al. 1976). However, although a number of plant parasitic nematodes are reported to be associated with wheat, only a few species are economically important. In surveys conducted in Mexico, *P. thornei* was found to be an economically important species, resulting in yield losses up to 40% (Nicol and Ortiz-Monasterio 2004, Lawn and Sayre 1992). More than 60 nematode species, among them *P. thornei*, are reported to be associated with maize in different parts of the world (McDonald and Nicol 2005). The presence of parasitic nematodes in soil per se does not mean that crop yield will be adversely affected. The population may be below the damage threshold, and the environment plays a paramount role in the long-term effect of nematodes on plant yield (Ramakrishna and Sharma 1998). Yeates et al. (1999) suggest that manipulation of the resource base can have important multitrophic effects and probably not all nematode species react equally to tillage and mulching. In research conducted in the central Highlands of Mexico (Govaerts et al. 2007a, 2006a) parasitic nematodes fared better in conventionally tilled situations; under zero tillage populations decreased. The number of non-plant parasitic nematodes increased under zero tillage with residue retention, compared to any combination of conventional tillage or residue removal treatments. Residue retention decreased the number of *P. thornei* in both maize and wheat. This result is not surprising, as many of the non-plant parasitic species evaluated feed on bacteria that are likely to increase in number because of the additional soil cover (Yeates et al. 1999). In terms of pest control, Stirling (1999) suggested that populations of natural enemies of parasitic nematodes would be enhanced under conditions of minimal soil disturbance. Therefore, abundance and population structure of free-living nematodes were considered potential bio-indicators of soil quality (Rahman et al. 2007, Griffiths et al. 1994, Ettema and Bongers 1993, Freckman and Ettema 1993, Bongers 1990).

7.4.2 Soil meso- and macrofauna

From a functional point of view, soil macrofauna can be divided into two functional guilds: litter transformers (comprised by large arthropods and also soil mesofauna) and ecosystem engineers (comprised mainly by termites and earthworms) (Lavelle 1997). Mites, springtails, epigeic enchytraeid worms and some earthworm species, isopods, millipedes and an array of insect larvae are among the most important meso- and macrofauna transforming the above ground litter entering the soil (Brussaard 1998). Litter transformers have a minor effect on soil structure. Their activities concentrate over the soil surface where they physically fragment litter and deposit mainly organic faecal pellets. Ecosystem engineers on the other hand usually ingest a mixture of organic matter and mineral soil and are responsible for the gradual introduction of dead organic materials into the soil. These organisms strongly influence soil structure and aggregation (Lavelle 1997).

7.4.2.1 Soil mesofauna

Soil microarthropods consist mainly of springtails (Collembola) and mites (Acari) and form the major part of the soil mesofauna (Kladivko 2001). These groups span a range of trophic levels, consuming plant litter, microflora, and other mesofauna (Wardle 1995). Springtails are usually inhibited by tillage disturbances (Miyazawa et al. 2002, Wardle 1995), although some studies have shown the opposite or no effect (Reeleder et al. 2006). Mites exhibit a wider range and more extreme responses to tillage than microbial groups, with moderate to extreme increases or decreases having been found (Wardle 1995). Reeleder et al. (2006) found that total mite population was more affected by cover crop than by tillage practice, with higher populations in a system with a rye cover crop- considerably higher than in a system with a fallow period. The different taxonomic groups of mites appear to respond differently to tillage disturbance, which explains some of the varied responses. The prostrigmatic, cryptostigmatid (Oribatid) and mesostigmatid mites can be moderately to extremely inhibited by tillage compared with zero tillage practices, whereas the astigmatid mites may be either inhibited or enhanced by tillage and appear to recover from tillage disturbances more rapidly (Reeleder et al. 2006, Wardle 1995). The effects of tillage on microarthropod populations are caused in part by the physical disturbance of the soil by tillage. Some individuals may be killed initially by abrasion during the tillage operation or by being trapped in soil clods after tillage inversion (Wardle 1995). Different orders of mites or species assemblages of springtails respond differently to the longer-term effects of tillage practices on soil moisture, pore continuity, and litter accumulation. It is also probable that microarthropod numbers are affected to some extent by the overall biomass of the trophic levels below them (Kladivko 2001).

The other main faunal group within the mesofauna is the enchytraeids. They are small, colorless worms that burrow extensively in the soil and can increase aeration, water infiltration, and root growth and may be either inhibited or stimulated by tillage (Cochran et al. 1994).

7.4.2.2 Soil macrofauna

Large organisms appear to be especially sensitive to agro-ecosystem management (Chan 2001, Folgarait et al. 1998, Black and Okwakol 1997, Kladivko et al. 1997, Robertson et al. 1994, Holt et al. 1993, Barnes and Ellis 1979) with less negative impacts on species with high mobility and higher population growth potential (Decaëns and Jiménez 2002). Tillage, through direct physical disruption as well as habitat destruction, strongly reduces the populations of both litter transformers and ecosystem engineers (Kladivko 2001). Residue incorporation could limit recolonization processes by soil biota due to redistribution of the food source as well as greater water and temperature fluctuations which reduces their active period in the soil (particularly under temperate climates). Although crop rotations could theoretically be beneficial for soil macrofauna populations through greater biomass returns to the soil (FAO 2003), concrete evidence is inconclusive (Hubbard et al. 1999, Rovira et al. 1987) and in general absent. In any case, crop rotations cannot compensate for the effects of tillage on soil biota population (Decaëns and Jiménez 2002).

7.4.2.2.1 Earthworms

The positive effects of earthworms are not only mediated by the abundance but also by the functional diversity of their communities. Bouché (1982) divided earthworms into epigeic (live above the soil and feed in the litter layers), anecic (feed on a mixture of litter and mineral soil and create vertical burrows with openings at the surface) and endogeic species (inhabit mineral soil horizons and feed on soil more or less enriched with organic matter). Earthworm species differ in their ecological behavior and thus have different effects on soils. For example, large earthworms produce large-sized and compact aggregates whereas small eudrilid earthworms produce small, fragile castings. The presence of both groups appears to be essential to maintain soil structure since experiments have shown that the absence of one or other of the groups resulted in important modifications of soil structure and associated physical properties (Blanchart et al. 2004). In fact, unbalanced combinations of earthworms due to disturbances were found to reduce infiltration and cause severe erosion in the Amazon (Chauvel et al. 1999). This depends on the degree of species redundancy and the interactions with other soil macroinvertebrates, and how these are modified by management perturbations.

In general, earthworm abundance, diversity and activity have been found to increase under conservation agriculture when compared to conventional agriculture (Kladivko 2001, Chan 2001, Kladivko et al. 1997, Barnes and Ellis 1979, Gerard and Hay 1979). Few exceptions have been recorded (Nuutinen 1992, Wyss et al. 1992) and are probably related to type and timing of tillage as well as original species assemblage (Chan 2001). Although tillage is the main factor perturbing earthworm populations, mulched crop residues are also important since earthworms do not have the ability to maintain a constant water content (their water content is greatly influenced by the water potential of the surrounding media) (Edwards and Bohlen 1996).

Earthworm castings promote the creation of stable organo-mineral complexes with reduced decomposition rates (although characterized by enhanced mineralization during the first few hours to days) and favor soil macroaggregate stability (> 250 µm) if allowed to dry or age (Six et al. 2004, Marinissen and Dexter 1990, Shipitalo and Protz 1988). However, when fresh casts are exposed to rainfall, they can be easily dispersed and contribute to soil erosion and nutrient losses (Blanchart et al. 2004, Binet and Le Bayon 1999). Besides, during gut transit, organic materials are intimately mixed and become encrusted with mucus to create nuclei for microaggregate inception (Six et al. 2004, Barois et al. 1993, Shipitalo and Protz 1988). Earthworm activity is also reported to be related to increased infiltration in zero tillage soils through enhanced soil surface roughness (Blanchart et al. 2004) and increased soil macroporosity, especially when populations are significant (Shipitalo and Butt 1999, Edwards and Shipitalo 1998, Chan and Heenan 1993, Trojan and Linden 1992, Zachmann et al. 1987, Ehlers 1975).

7.4.2.2.2 Termites and ants

There is less literature available focusing on termites and ants in agro-ecosystems than on earthworms. It has, however, been proposed that ants are as important as earthworms in soil transformation (Gotwald 1986). Termites and ants are predominant in arid and semi-arid regions where earthworms are normally absent or scarce (Lobry de Bruyn and Conacher 1990).

In general, ants and termites (both subterranean and mound building species) increase infiltration by improving soil aggregation and porosity (Nkem et al. 2000, Lobry de Bruyn and Conacher 1990) even in situations of low organic matter and clay contents (Mando and Miedema 1997). Soil-feeding termites also form microaggregates either by passing soil material through their intestinal system and depositing it as faecal pellets or by mixing the soil with saliva using their mandibles (Bignell and Holt 2002, Jungerius et al. 1999). Stability of such structures depends on the amount of organic mater incorporated into them which varies by species (Six et al. 2004). Ants changed soil quality in cotton fields, particularly in areas near and adjacent to ant hills and foraging paths by increasing organic matter, sand and silt and reducing clay, Ca, Mg, K and Na concentrations (Nkem et al. 2000, Hulugalle et al. 1995). Nkem et al. (2000) also noted high compaction on the tops of mounds, which could be explained by the process of nest construction and the binding of soil particles and could be limit plant root penetration and seed germination. They hypothesized that nutrients in active mounds are not readily accessible to plants and agents of degradation, thereby maintaining a source for subsequent redistribution when the mound is abandoned. Management options which favor ants and termites populations, such as residue mulch and reduced or zero tillage, have been identified as key factors in improving the topsoil in agro-ecosystems, even in the degraded conditions of the Sahel (Mando and Miedema 1997). However, given their patchy and physically restricted distribution, it is not clear if ant and termite activity has relevant effects at the field level. Moreover, their positive effect on soil structure can be counteracted by a negative effect on crop yields and residue retention through herbivorous activity.

7.4.2.2.3 Arthropods

Not all arthropods are litter transformers, although most concentrate their activities above or within the topsoil. In spite of the different roles they play in the food web, most arthropods take part, at least partially, in organic matter incorporation through burrowing and food relocation thereby improving the soil structure (Zunino 1991). Theoretically, arthropods (Coleoptera and Araneae) are favored by conservation agriculture conditions given litter presence on the soil surface which constitutes a food source for many arthropods (directly and indirectly through herbivorous insects present in higher numbers) (Kladivko 2001) and due to higher niche availability (Ferguson and McPherson 1985). Species diversity of all arthropod guilds is generally higher in conservation agriculture with increases in both soil- and litter-inhabiting arthropods compared to conventional tillage (Stinner and House 1990). Sunderland and Samu (2000) also found that spider abundance increased by 80%, largely through population diversification, although exceptions have, of course, being found. Holland and Luff (2000) found no relevant differences in carabid beetles incidence in different tillage systems. Interestingly, various authors (Holland and Reynolds 2003, Marasas et al. 2001, Stinner and House 1990, House and Stinner 1983) found an increased presence of predators (spiders as well as carabid and staphylinids beetles) compared to phytophagous species under zero tillage systems. This has strong implications for pest management under conservation agriculture and deserves further research.

7.5 SOIL QUALITY AND CROP PRODUCTION

Land quality and land degradation affect agricultural productivity, but quantifying these relationships has been difficult (Wiebe 2003). However, it is clear that the necessary increase in food production will have to come from increases in productivity of the existing land rather than agricultural expansion, and that restoration of degraded soils and improvement in soil quality will be extremely important to achieve this goal. However, the rate of increase in crop yields is projected to decrease, especially in developing countries where natural resources are already under great stress (Lal 2006). The effects of soil degradation or regeneration, and therefore increased or reduced soil quality, on agricultural productivity will vary with the type of soil, cropping system and initial soil conditions, and may not be linear (Scherr 1999). The impacts of degradation on productivity are sensitive to farmer decisions (Wiebe 2003), and soil degradation in all its nefarious forms is eroding crop yields and contributing to malnourishment in many corners of the globe (Science, 11 June 2004, p 1617).

The effects of soil quality on agricultural productivity are greater in low-input rain fed production systems than in highly productive systems (Scherr 1999). Govaerts et al. (2006b) determined the soil quality of plots after more than 10 years of different tillage and residue management treatments. There was a direct and significant relation between the soil quality status of the soil and the crop yield, and zero tillage with crop residue retention showed the highest crop yields as well as the highest soil quality status (Govaerts et al. 2006b, Govaerts et al. 2005). In contrast, the soil under zero tillage with crop residue removal showed the poorest soil quality (i.e. low contents of organic C and total N, low aggregate stability, compaction, lack of moisture and acidity) and produced the lowest yields, especially with a maize monoculture (Fuentes et al. 2008, Govaerts et al. 2006b).This is in line with other studies: for instance Ozpinar and Cay (2006) found that wheat grain yield was greater when tillage practices resulted in improved soil quality as manifested by higher soil organic carbon content and total nitrogen. Lal (Science, 11 June 2004, p 1623-1627) calculated the relations between increases in SOC and its concomitant improvements in water and nutrient holding capacity, soil structure, and biotic activity and grain yield and found several positive relations. Also the reverse relation has been reported by several authors: reduced physical soil quality that results in increased erosion potential caused yield reductions of 30 to 90% in shallow lands of West Africa (Lal 1987, Mbagwu et al. 1984). Yield reduction in Africa due to past soil erosion may range from 2 to 40%, with a mean loss of 8.2% for the continent (Lal 1995). The actual loss may depend on weather conditions during the growing season, farming systems, soil management, and soil ameliorative input used. Globally, losses in food production caused by soil erosion are most severe in Asia, Sub-Saharan Africa, and elsewhere in the tropics (Lal 1998).

Lower potential production due to degradation may not show up in intensive, high-input systems until yields are approaching their ceiling (Scherr 1999). Sayre et al. (2005) report on a wheat-maize rotation in a long-term sustainability trial under irrigated conditions in northwestern Mexico that compared different bed planting systems (conventional tilled beds and permanent raised beds). Residue management varied from full to partial retention, as well as residue burning. Yields differences between management practices only became clear after 5 years (10 crop cycles), with a dramatic and sudden reduction in the yield of permanent raised beds where all residues had been routinely burned. In contrast to rainfed low rainfall areas, in irrigated agricultural systems, the application of irrigation water appears to ‘hide or postpone’ the expression of the degradation of many soil properties until they reach a level that no longer can sustain high yields, even with irrigation (Sayre et al. 2005). The reduced yields reported after five years with permanent beds where residues were burned, were related to a significant decrease in stable macroaggregation and soil microbial biomass (Limon-Ortega et al. 2006). In high-input systems, the decreased soil quality status of management practices is reflected in reduced efficiency of inputs (fertilizer, water, biocides, labour) resulting in higher production costs to maintain the same yield levels, rather than in lower yields as such (Scherr 1999).

In the Mexican highlands improved high-yielding wheat varieties yielded double under conservation agriculture compared to the farmer practice or zero tillage with residue removal, all with the same fertilizer inputs (Govaerts et al. 2005). Thus, future food production targets can only be met when the potential benefits of improved varieties are combined with improved soil management technologies. The latter include, first and foremost, restoration of degraded and desertified soils, improvement of soil structure and enhancement of soil quality and health through increases in SOM reserves, conservation of water in the root zone, and control of soil erosion. Once soil quality and soil health are restored, then, and only then, are the benefits of improved varieties and chemical fertilizers realized. In an 18-year experiment in Kenya, maize and bean yields averaged 1.4 t ha^{-1} $year^{-1}$ without external input and 6.0 t ha^{-1} $year^{-1}$ when crop residue was retained and fertilizer and manure applied (Kapkiyai et al. 1999). This is the type of quantum jump in crop yields needed at the continental scale to ensure food security in sub-Saharan Africa (SSA). The vicious cycle of declining productivity due to depleted SOC stock will have to be broken by improving soil quality through SOC sequestration. This will be an important and necessary step to free much of humanity from perpetual poverty, malnutrition, hunger, and substandard living (Science 11, June 2004, p 1623-1627). Rather than the seed-fertilizer package, it is crucial to adopt the strategy of integrated soil fertility management that is based not only on recycling nutrients through enhanced productivity and soil organic carbon levels, but also appreciation of the importance of soil physical an biological fertility: a soil may be rich in nutrients but if it has a poor physical structure and lacks the biological elements to improve this structure, crop productivity will be low. Conservation agriculture, that combines reduced tillage, crop residue retention, and functional crop rotations, together with adequate crop and system management, permit the adequate productivity, stability and sustainability of agriculture.

7.6 CONCLUSIONS

Conservation agriculture improves soil aggregation compared to conventional tillage systems and zero tillage without retention of sufficient crop residues in a wide variety of soils and agro-ecological conditions. The effect of conservation agriculture on total porosity and pore size distribution is less clear. The conversion of conventional to zero tillage can result in the loss of total pore space as indicated by an increase in bulk density. However, the loss of porosity is generally limited to the plough layer. There is some evidence that the porosity in the top 5 cm of the profile may be greater under zero tillage when residue is retained. The extent of increase may be a function of enhanced macrofaunal activity and the build-up of organic matter at this depth, indicating the importance of crop residue retention when adopting zero tillage. Additionally, the adoption of controlled traffic when converting to zero tillage is important in limiting the possible loss of pore pace. Where total porosity decreases in conservation agriculture compared to conventional practices, this decrease seems to take place mainly in the macropore class with a concomitant increase in micro- and mesopore classes. Despite the possible decrease in macroporosity in conservation agriculture compared to conventional practices, macropore interconnectivity is reported to be higher with conservation agriculture because of biopores, and the maintenance of channels created by roots. More research is needed to determine the effect of the adoption of conservation agriculture on total porosity, pore size distribution and connectivity and related hydraulic soil properties in different soils and agro-ecological conditions.

Infiltration is generally higher and runoff reduced in zero tillage with residue retention compared to conventional tillage and zero tillage with residue removal due to the presence of the crop residue cover that prevents surface crust formation and reduces the runoff velocity, giving the water more time to infiltrate. Soil evaporation is reduced by surface residue cover and increased by tillage. Soil moisture is conserved and more water is available for crops with conservation agriculture. The increased aggregate stability and reduced runoff in conservation agriculture result in a reduction of water erosion. Also the susceptibility of soils to wind erosion is reduced.

Due to the insulation effect of surface residue, temperature fluctuations are smaller in zero tillage with residue retention than in conventional tillage and zero tillage without residue retention. Tilled soils heat faster in the spring due to the reduction of surface residue cover, the drying effect of tillage and the creation of air pockets in which evaporation occurs. In temperate areas, the lower temperatures in conservation agriculture than in conventional tillage can slow down early crop growth and lead to crop yield declines. In tropical hot soils, however, the surface residue cover reduces soil peak temperatures that are too high for optimum growth and development to an appropriate level, favouring biological activity, initial crop growth and root development.

The combination of reduced tillage with crop residue retention increases the SOC in the topsoil. Especially when crop diversity and intensity are increased, evidence points to the validity of conservation agriculture as a carbon storage practice and justifies further efforts in research and development. As the C-cycle is influenced by conservation agriculture, also the N cycle is altered. Adoption of conservation agriculture systems with crop residue retention may result initially in N immobilization. However, rather than reducing N availability, conservation agriculture may stimulate a gradual release of N in the long run and can reduce the susceptibility to leaching or denitrification when no growing crop is able to take advantage of the nutrients at the time of their release. Also crop diversification, an important component of conservation agriculture, has to be seen as an important strategy to govern N availability through rational sequences of crops with different C/N ratios. Tillage, residue management and crop rotation have a significant impact on micro- and macronutrient distribution and transformation in soils. The altered nutrient availability may be due to surface placement of crop residues in comparison with incorporation of crop residues with tillage. Conservation agriculture increases availability of nutrients near the soil surface where crop roots proliferate. Slower decomposition of surface placed residues prevents rapid leaching of nutrients through the soil profile. The response of soil chemical fertility to tillage is site-specific and depends on soil type, cropping systems, climate, fertilizer application and management practices. However, in general nutrient availability is related to the effects of conservation agriculture on SOC contents. The CEC and nutrient availability increase in the topsoil. Numerous studies have reported higher extractable P levels in zero tillage than in tilled soil largely due to reduced mixing of the fertilizer P with the soil, leading to lower P-fixation.

Conservation agriculture induces important shifts in soil fauna and flora communities. The different taxonomic mesofauna groups respond differently to tillage disturbance and changed residue management strategies. However, in general tillage, through direct physical disruption as well as habitat destruction, strongly reduces macro-fauna including both litter transformers and ecosystem engineers. When reduced tillage is combined with residue retained on the soil surface, this provides residue-borne pathogens and beneficial soil micro-flora species with substrates for growth, and pathogens are at the soil surface, where spore release may occur. This can induce major shifts in disease pressure in conservation agriculture systems. However, in general, the combination of crop residue retention with reduced tillage also results in an increased functional and species diversity. Functional diversity and redundancy which refers to a reserve pool of quiescent organisms or a community with vast interspecific overlaps and trait plasticity, are signs of increased soil health, and allow an ecosystem to maintain a stable soil function. Larger microbial biomass and greater microbial activity, as supported by conservation agriculture, can result in soils exhibiting suppression towards soil-borne pathogens and increased possibilities of integrated pest control are created.

The needed yield increases, production stability, reduced risks and environmental sustainability can only be achieved through management practices that result in an increased soil quality in combination with improved crop varieties. The above outlined evidence for the improved soil quality and production sustainability with well implemented conservation agriculture systems is clear, although research remains inconclusive on some points. At the same time, the evidence for the degradation caused by tillage systems is convincing especially in tropical and sub-tropical conditions and for biological and physical soil quality. Therefore, even though we do not know how to manage functional conservation agriculture systems under all conditions, the underlying principles of conservation agriculture should provide the foundation upon which the development of new practices is based, rather than be considered a parallel option to mainstream research activities that focus on improving the current tillage-based production systems.

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