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Conservation agriculture, improving soil quality for sustainable production systems?

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1. Introduction

1.1. Food production and land degradation

Human efforts to produce ever-greater amounts of food leave their mark on the environment. Persistent use of conventional farming practices based on extensive tillage, especially when combined with removal or in situ burning of crop residue, has magnified soil erosion losses and the soil resource base has been steadily degraded. It has been estimated that human activity is responsible for the loss of 26 billion tons of topsoil per year, which is 2.6 times the natural rate of soil degradation. Erosion has been estimated to cause USD \$44 billion a year in damage to farmland, waterways, infrastructure, and health. Crop yields in the US would drop 8% per year if farmers failed to replace lost nutrients and water (Pimentel et al., 1995).

Another direct consequence of farmers' persistent use of traditional production practices is rapidly increasing production costs; the costs of inputs such as improved varieties and fertilizers continue to increase and farmers make inefficient use of them.

1.2. Conservation agriculture

Nowadays, people have come to understand that agriculture should not only be high yielding, but also sustainable. Conservation agriculture (CA) has been proposed as a widely adapted set of management principles that can assure more sustainable agricultural production. Conservation agriculture is a broader concept than conservation tillage, a system where at least 30% of the soil surface is covered with crop residues after seeding of the next crop. In CA, the emphasis lies not only on the tillage component but on the combination of the following three principles:

1. Reduction in tillage: The objective is to achieve zero tillage (i.e., no tillage at all) 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;
- reduce water run-off and evaporation;
- improve water productivity; and
- enhance soil physical, chemical, and biological properties associated with long-term sustainable productivity

3. Use of crop rotations: The objective is to employ diversified crop rotations to:

- help moderate/mitigate possible weed, disease and pest problems;
- utilize the beneficial effects of some crops on soil conditions and on the productivity of the next crop; and
- provide farmers with economically viable options that minimize risk.

These CA principles are applicable to a wide range of crop production systems from low-yielding, dry, rainfed conditions to high-yielding, irrigated conditions. However, the application of the principles of CA will be very different from one situation to another. Specific and compatible management components such as pest and weed control tactics, nutrient management strategies, rotation crops, 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 (Figure 1) 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.

1.3. Soil quality

When evaluating an agricultural management system for sustainability, the central question is: which production system will not exhaust the natural resources, will optimize soil conditions and will reduce food production

vulnerability, while at the same time maintaining or enhancing productivity? Soil quality is the practical translation of this concept of sustainability. Soil quality can be defined as follows:

- The capacity of a specific soil type to function, within naturally managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation
- The degree of fitness of a soil for a specific use
- The ability of the soil to maintain high productivity, without significant soil or environmental degradation.

Evaluation of soil quality is based on the physical, chemical, and biological characteristics of the soil. Management factors such as tillage and residue management can modify the soil quality. Changes in soil quality are, however, not only associated with management, but also with the environmental context, such as temperature and precipitation. 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 all the alternative systems are compared over time. This kind of comparison is useful for determining the impact of management systems that have been in place for some period of time.

2. Influence of conservation agriculture on physical soil quality

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. It has been defined 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 (Figure 2). Soil structure is often expressed as the degree of stability of aggregates.

Soil structural stability is the ability of aggregates to remain intact when exposed to different stresses. Shaking of aggregates on a wire mesh both in air (dry sieving) and in water (wet sieving) is commonly used to measure aggregate stability. With dry sieving, the only stress applied is the one from the sieving, while with the wet sieving the samples are additionally exposed to the power of the water (slaking). Therefore, the mean weight diameter (MWD) of aggregates after dry sieving is generally larger than the MWD after wet sieving. In the following, we will discuss the three elements of CA and their influence on physical soil quality.



Fig. 1. Permanent raised beds with furrow irrigation. The 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.



Fig. 2. Soil aggregates; on the left, clear structure and aggregates with soil fauna present; on the right, dense structure and fewer aggregates than on the left.

2.1.1. Influence of tillage

Zero tillage with residue retention improves dry aggregate distribution compared to conventional tillage. The effect of zero tillage on water stability is even more pronounced, with a higher MWD for wet sieving reported for a wide variety of soils and agro-ecological conditions (for example Figure 3).

In cases when conventional tillage results in good structural distribution, the structural components are still weaker at resisting water slaking than in zero tillage situations with crop residue retention. Thus, soils under zero tillage with residue retention become more stable and less susceptible to structural deterioration, while

conventionally tilled soils are prone to erosion (Figure 4). This is a result of the direct and indirect effects of tillage on aggregation:

- Physical disturbance of soil structure through tillage results in a direct breakdown of soil aggregates and an increased turnover of aggregates.
- Tillage also results in breakdown of fragments of roots and mycorrhizal hyphae, which are major binding agents for macroaggregates.
- The residues lying on the soil surface in CA protect the soil from raindrop impact.
- During tillage, a redistribution of the soil organic matter takes place. Small changes in soil organic carbon can influence the stability of macroaggregates.

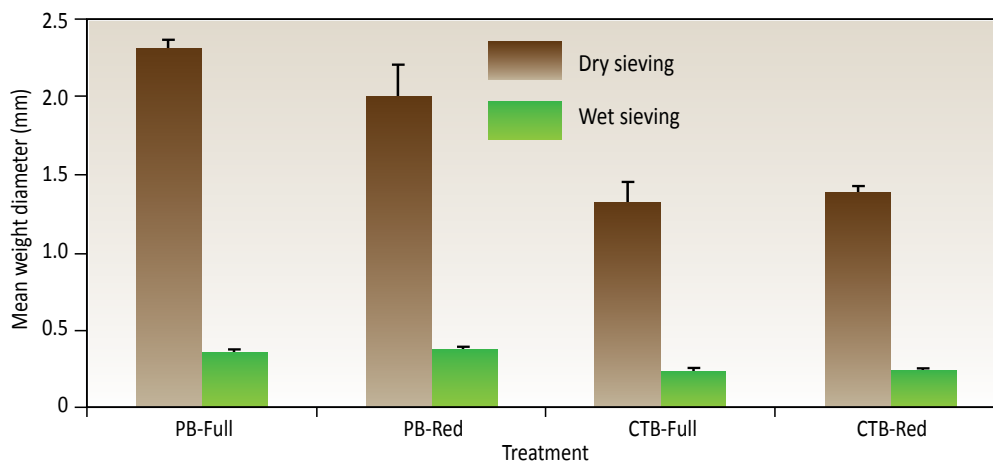


Fig. 3. Effect of tillage and irrigation management on mean weight diameter of soil aggregates obtained by dry and wet sieving for the 2008/09 crop cycle in CIMMYT's long-term sustainability experiment, Yaqui Valley, Mexico (adapted from Verhulst et al., 2011). Error bars represent the standard error of the mean. PB = permanent raised beds; CTB = conventionally tilled beds; Full = full irrigation; Red = reduced irrigation.

- Soil organic matter can increase both soil resistance and resilience to deformation, and improve soil macroporosity.
- Tillage reduces macrofauna populations (e.g., earthworms), compared to CA systems, which decreases the potentially positive effects of macrofauna on soil aggregation.

2.1.2. Influence of residue management

As organic matter is a key factor in soil aggregation, the management of previous crop residues is 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. The return of crop residue to the soil surface not only increases the aggregate formation, but it also decreases the breakdown of aggregates by reducing erosion and protecting 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. It was also found that burning stubble lowered the water stability of aggregates in the fractions >2 mm and <50 µm. However, it must be noted that partial residue removal kept aggregation within acceptable limits. 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.

2.1.3. Influence of crop rotation

Altering crop rotation can influence soil organic carbon by changing the quantity and quality of organic matter



Fig. 4. Differences in aggregation between conservation agriculture (left) and conventional management (right). After 5 years of zero tillage on permanent raised beds, the soil had significantly more stable aggregates compared to conventional tillage. (Photo taken by Castellanos-Navarrete, A., 2006).

input and thus has the potential to alter soil aggregation indirectly. Crops can affect soil aggregation by their root systems because plant roots are important binding agents at the scale of macroaggregates. A soil under wheat was found to have more large macroaggregates than a soil under maize (Lichter et al., 2008). 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 network could positively influence aggregate formation and stabilization. Also, soil microbial biomass and bacterial diversity can influence aggregate formation, and these can be influenced by crop rotation too. However, few studies have reported on the influence of crop rotation on soil aggregation.

2.2. Soil porosity

Pores are of different sizes, shapes, 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. The pores are created by abiotic (e.g., tillage and traffic, freezing and thawing, drying and wetting) and by biotic factors (e.g., root growth, burrowing fauna). The changes in pore characteristics primarily reflect changes in the form, magnitude and frequency of stresses imposed on the soil, the placement of crop residues, and the population of micro-organisms and fauna in the soil.

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. The effect of tillage and residue management on soil density is mainly confined to the topsoil (plough layer). In deeper soil layers, soil bulk density is generally similar in zero and conventional tillage.

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. In short-term experiments, there is no clear effect of the management system on bulk density – most studies found no significant differences in soil bulk density between zero tillage and conventional tillage. The results of the effect of different tillage practices on bulk density in experiments that have run for approximately 10 years are variable. In one experiment in New Zealand, an increase in bulk density under zero tillage compared

with conventional tillage was measured after 10 years in an imperfectly drained loess soil. However, a significantly more compacted soil under zero tillage compared to conventional tillage did not have an adverse effect on crop yield. Other studies found a lower bulk density in zero tillage than in conventional tillage at a depth of 3–7 cm. The difference was not evident in the lower soil layers (Horne et al., 1992).

Differences in bulk density between tillage systems in the longer term (>15 years) have been somewhat more consistent. It has mostly been observed that soil bulk density is higher in the surface layer of zero tillage than conventional tillage, 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. The top 3 cm of the soil can have a lower bulk density under zero tillage, which is attributed to the development of an organic-rich mulch and possibly enhanced faunal activity.

A 15-year field experiment in China showed the evolution of the soil density under different tillage systems (Li et al., 2007):

- In the first 6 years, 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
- However, in the following 5 years, mean soil bulk density of the two treatments were similar
- 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 organic carbon, increased biotic activity, and improved structure.

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 space.

Reports on the effect of crop rotation and residue management on soil porosity are sparse. It seems that in long-term experiments, cropping systems that return more crop residue decrease bulk density and increase the total and effective porosity than systems that leave fewer residues. The more mulch left on the surface, the lower the bulk density, and this effect is very clear in the 0–3 cm and to a lesser extent in the 3–10 cm layers (Blanco-Canqui and Lal, 2007). The retention of crop residue in the field is important to prevent compaction when conventionally tilled fields are converted to zero tillage.

2.2.2. Pore size distribution and pore continuity

The changes in total porosity introduced by management are related to the alterations in pore size distribution. Total porosity of soils is distributed among different pore size classes and different size classes fulfill different roles in aeration, infiltration, drainage and storage of water, and offer different mechanical resistance to root growth. The three classes of pores are shown in Table 1, with their size and function.

In general, micro- and meso-porosity is reported to be higher in zero tillage compared to conventional tillage, but in some cases no effect of tillage is observed. The effect of residue management and crop rotation on pore size distribution is not often investigated; however, one study reported a higher volume of mesopores in the 0–3 cm layer in zero tillage with residue retention than in zero tillage without residue retention (Blanco-Canqui and Lal, 2007).

Macropores are important for water flux and infiltration in both saturated and unsaturated conditions. In addition, a soil matrix with macropores offers greater potential for undisturbed root growth because the roots can bypass the zones of high mechanical impedance.

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-

Table 1. Pore classes with diameter and primary function

| Name | Diameter | Primary function |
|------------|-----------|--|
| Macropore | >30 μm | Water flow during infiltration and drainage, soil aeration, place of initiation of root growth |
| Mesopore | 0.2–30 μm | Storage of water for plant growth |
| Micropores | <0.2 μm | Microbiological activity |

induced compaction. However, this compaction may be compensated for by progressive creation of macropores from roots and faunal activity with time. 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.

Water infiltration, retention, and flow not only depend on the quantity and size of pores but also on the interconnectivity and shape of pores. Changes in the morphology of pores reflect changes in the processes that create these pores. Irregular and elongated shaped pores, >1,000 μm in diameter and length, are greater in number in conventional compared to zero tillage at a depth of 0–20 cm. This can be attributed to annual mixing and homogenization by the plough. A greater proportion of macropores oriented in the horizontal direction in the 5–15 cm depth was observed under zero tillage than under conventional tillage (VandenBygaert et al., 1999). Biopores created by roots and fauna such as earthworms can be maintained in the plough layer in the absence of annual tillage. These rounded pores >500 μm are more frequent in the zero tillage systems after a few years, even when the total number of macropores >1,000 μm was much greater under conventional tillage (VandenBygaert et al., 1999). This can be attributed to the maintenance of root and earthworm channels under zero tillage through the years, while these are destroyed annually under conventional tillage. The earthworm channels with excrement infillings were abundant in the zero tillage plots at all depths, but absent in conventionally tilled plots.

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, which is the result of an increased number of biopores. However, the results of different studies are not consistent. Although in many studies a higher hydraulic conductivity was observed under zero tillage compared to conventional tillage, it has also been reported that there was no significant effect of tillage and residue management. The different results may be partly due to the difficulty of measuring hydraulic conductivity when 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. This may cause high variation in conductivity values at small scales due to macropores, and other structural attributes that are left intact by the absence of tillage. 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.

Soil management practices that increase the organic matter content in the soil could have a positive impact on soil water-holding capacity. Water-holding capacity has been observed to increase with increases in soil organic matter, meaning CA has the potential to increase water-holding capacity.

2.4. Soil water balance

2.4.1. Infiltration and runoff

Despite 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 effects 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 formation of surface seals or crusts. The presence of crop residues over the soil prevents aggregate breakdown by direct raindrop impact as well as by rapid wetting and drying of soils
- Aggregates are also more stable under zero tillage with residue retention compared to conventional tillage and zero tillage with residue removal. This means that wind erosion and rapid wetting (i.e., slaking) cause less aggregate breakdown, preventing surface crust formation
- The residues left on the surface 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.

McGarry et al. (2000) found that time-to-pond, final infiltration rate, and total infiltration were significantly larger with zero tillage with residue retention than with conventional tillage (Figure 5). This was ascribed 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.

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. Tillage moves moist soil to the surface, increasing losses to drying. Hence, tillage disturbance of the soil surface increases soil water evaporation compared to untilled areas. The amount of energy the soil surface receives is influenced by canopy and residue cover. Residue and mulches reduce soil water evaporation by reducing soil temperature, impeding vapor diffusion, absorbing water vapor onto mulch tissue, and reducing the wind speed gradient at the soil-atmosphere interface. The rate of drying of the soil is determined by the thickness of the residue together with the atmospheric evaporative potential.

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 non-uniform distribution of residue.

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. Mulching helps conserve soil water in a season with long periods without rain. Soil water content increases with increases in surface cover. More soil water enables crops to grow during short-term dry spells. Therefore, zero tillage with

residue retention decreases the frequency and intensity of short midseason droughts. Thus, tillage and residue management may significantly affect crop yields in areas or seasons with poor rainfall distribution.

2.5. Soil erosion

2.5.1. Water 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. Soil erosion is a function of erosivity and erodibility. Erosivity is related to the physical characteristics of rainfall at the soil surface and runoff velocity. Erosivity is therefore affected by the crop residues (e.g., in zero tillage with residue retention) that break the raindrop impact and slow down runoff, reducing erosion. Erodibility of the soil is related to the physical characteristics of the soil. Aggregate breakdown is a good measure of soil erodibility, as breakdown to finer, more transportable particles and microaggregates increases erosion risk. CA practices have a higher aggregate stability compared to conventional practices or zero tillage fields without residue retention. This results in lower soil erosion potential for CA. The positive effect of CA on reduced erodibility is further enhanced by the reduced amount of runoff.

In summary, CA results in erosion rates much closer to soil production rates than conventional tillage and therefore could provide a foundation for sustainable agriculture.

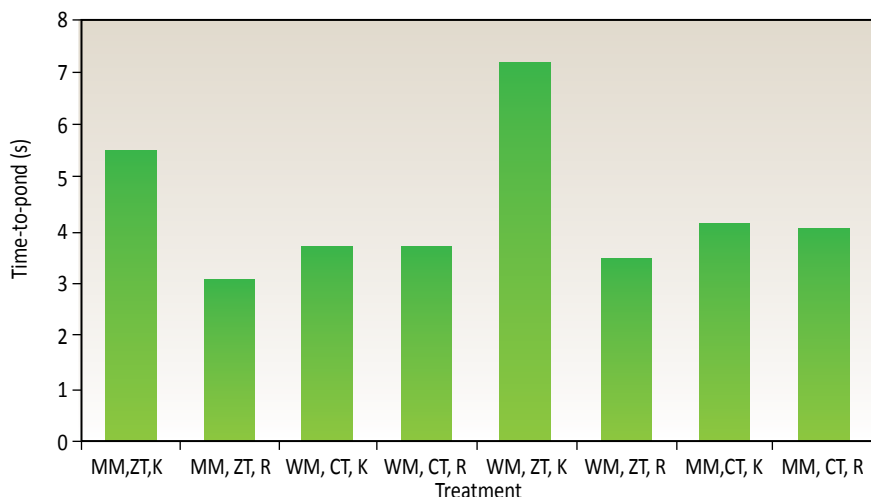


Fig. 5. Effect of tillage, crop rotation and crop residue management on time-to-pond during the crop cycle for maize for 2004 in CIMMYT's long-term sustainability trial, El Batán, Mexico. W = wheat; M = maize; K = the residue is kept in the field; R = residue is removed; CT = conventional tillage; ZT = zero tillage. Treatment means with a different letter within the same data series differ significantly according to t-test (LSD) at $P < 0.05$ (adapted from Govaerts et al., 2009).

2.5.2. Wind erosion

Susceptibility of soils to wind erosion largely depends on the aggregate size distribution and is determined by dry sieving. The percentage of aggregates with sizes smaller than 0.84 mm is considered the soil fraction susceptible to be transported by wind. This erodible fraction is twice as large in weight in conventional tillage than in zero tillage, indicating that conventional tillage is much more prone to wind erosion (Singh and Malhi, 2006). Also, it has been shown that the erodible fraction in conventional tillage increases with time, while the fraction remained unchanged in zero tillage. 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.

2.6. Soil temperature

The balance between incoming and outgoing radiation determines the energy available for heating the soil. 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. Surface residue reflects solar radiation and insulates the soil surface. 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. 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. Soil temperatures in surface layers can be significantly lower (often between 2°C and 8°C) during daytime (in summer) in zero tilled soils with residue retention compared to conventional tillage. During night time, the insulation effect of the residue leads to higher temperatures so there is a lower difference in soil temperatures in 24 hours with zero tillage. In tropical hot soils, mulch cover reduces soil peak temperatures that are too high for optimum growth and development to an appropriate level, favoring biological activity, initial crop growth, and root development during the growing season.

In temperate areas, however, lower temperatures create unfavorable cool soils, slowing down early crop growth and leading to lower crop yield, especially if late frost

occurs. In these temperate areas, it is suggested to use a residue-free strip without soil disturbance over the row center. This strip can provide more heat input to the soil surface at the row center, and has no adverse effects on the soil water content.

3. Influence of conservation agriculture on chemical soil quality

3.1. Soil organic carbon

Soil organic carbon (SOC) has been proposed as a primary indicator of soil quality, especially the SOC concentration of surface soil. 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 partitions the flux of gases into and out of the soil. Surface organic matter is essential for erosion control, water infiltration, and conservation of nutrients.

3.1.1. Total soil organic carbon content

When comparing SOC in different management practices, several factors have to be taken into account:

1. Bulk density can increase after conversion from conventional tillage to zero tillage. If samples are taken at 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 zero tillage.
2. Tillage practices 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 SOC content in the deeper layers of tilled plots where residue is incorporated through tillage.

Because of these reasons, SOC contents under zero tillage compared to conventional tillage can be overstated if the entire plough depth is not considered.

3.1.1.1. Influence of tillage practice on soil organic carbon

The influence of the different components comprising CA (reduced tillage, crop residue retention and crop rotation) on SOC is not clear. However, some factors that play a role can be distinguished:

- Differences in root development and rhizodeposits: Crop root-derived C may be very important.
- Soil bulk density and porosity: The use of zero tillage practices only enhances physical protection of SOC

where soil bulk density is relatively high and when the use of zero tillage management reduces the volume of small macropores.

- Climate: Management impacts are sensitive to climate in the following order from largest to smallest changes in SOC: tropical moist > tropical dry > temperate moist > temperate dry.
- The stabilization of C in microaggregates-within-macroaggregates: Occluded intra-aggregate particulate organic matter C in soil microaggregates contributes to long-term soil C sequestration in agricultural soils. These microaggregates-within-macroaggregates constitute relatively stable and secluded habitats for microorganisms.

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. 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.

3.1.1.3. Influence of crop rotation on soil organic carbon

Altering crop rotation can influence SOC by changing the quantity and the quality of organic matter input. Increased moisture conservation related to CA practices can result in the possibility of growing an extra cover crop right after 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. However, the increase in SOC concentration can be negated when the crop cover is incorporated in the soil.

Conservation agriculture can increase the possibility for crop intensification due to a faster turnaround time between harvest and planting (because the field needs hardly any preparation). Moreover, other cropping options may become available since the actual growing period can be increased by the decreased turnaround time 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.

In general, it has been observed that enhancing the 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) results in an increase in SOC. However, this increase in SOC was on average lower than the increase observed when changing from conventional to zero tillage. Enhancing crop rotation was still more effective in retaining C and N in soil than a monoculture system was.

The effect of crop rotation on SOC contents can be due to increased biomass 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. For instance, legume-based rotations contain greater amounts of aromatic C content (a highly biologically resistant form of carbon) below the plough layer than continuous maize (Gregorich et al., 2001).

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. To obtain an accumulation of soil organic matter (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 manure crop. If leguminous green manure (vetch) is included in the cropping system, the contribution of N₂ fixation of the vetch is the principal factor responsible for the observed C accumulation in the soil under zero tillage. Most accumulated C was derived from crop roots. Conventional tillage can reduce 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 or in gaseous form due to SOM mineralization stimulated by tillage.

3.1.2. Soil organic carbon fractionation

The following soil C fractions can be distinguished:

- the easily decomposable fraction, representing an early stage in the humification process
- material stabilized by physical-chemical mechanisms (intermediary)
- 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. The labile fraction plays a crucial role in the formation of aggregates and responds rapidly to changes in soil management because of its rapid turnover time. Therefore, it can be a good indicator of early changes in SOC. The labile fraction increases when tillage intensity reduces. This higher labile fraction accounts for most of the observed higher SOC concentration (0–10 cm) for zero tillage compared to conventional tillage (Six et al., 2001).

Crop rotation can influence the different C fractions. More diverse crop rotations lead to a greater proportion of fine POM than monoculture. The effect of the tillage system on light fraction C is smaller than the effect of cropping intensity.

3.2 Nutrient availability

Tillage, residue management, and crop rotation have a significant impact on nutrient distribution and transformation in soils, usually related to the effects of CA on SOC contents (see 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. The altered nutrient availability under zero tillage may be due to surface placement of crop residues in comparison with incorporation of crop residues with tillage. Slower decomposition of surface placed residues may prevent rapid leaching of nutrients through the soil profile. Under zero tillage, the number of continuous pores can be high, leading to more rapid passage of soluble nutrients deeper into the soil profile. The density of crop roots is usually greater near the soil surface under zero tillage compared to conventional tillage. This leads to a greater proportion of nutrients taken up from near the soil surface. However, the nutrient concentrations in plant tissues are usually not affected by tillage or crop combinations.

3.2.1 Nitrogen availability

The presence of mineral soil N available for plant uptake is dependent on the rate of C mineralization. The impact of reduced tillage with residue retention on N mineralization is not clear. Zero tillage with residue retention can be associated with a lower N availability because of greater immobilization by the residues left on the soil surface. The net immobilization phase when zero tillage is adopted could be transitory, as the higher immobilization of N reduces the opportunity for leaching and denitrification losses of mineral N.

3.2.1.1. Total nitrogen content

Effects of CA on total N content generally mirror those observed for total SOC as the N cycle is inextricably linked to the C cycle. Zero tillage and permanent raised beds have a significantly higher total N than conventional tillage (Govaerts et al., 2007a). Significant increases in total N have been measured with increasing additions of crop residue.

3.2.1.2. The influence of tillage practice on nitrogen mineralization

Tillage increases aggregate disruption, making organic matter more accessible to soil micro-organisms and increasing the release of mineral N from active and physically protected N pools. When tillage is reduced there are more stable macroaggregates. C and N in the microaggregates-within-macroaggregates are more protected. In general, the N mineralization rate increases when tillage decreases. The N mineralization rate also increases with an increasing rate of inorganic N fertilizer application. Residue management also determines the rate of N mineralization. In conventional tillage, the residue is incorporated into the soil, while it is left on the soil surface in zero tillage. Incorporated crop residues decompose 1.5 times faster than surface placed residues. However, the type of residues and the interactions with N management practices also determine C and N mineralization.

3.2.1.3. The influence of crop residues on nitrogen mineralization

The composition of residues left on the field will affect their decomposition. The C/N ratio is one of the most often used criteria for residue quality, together with initial residue N, lignin, polyphenols, and soluble C concentrations. During the decomposition of organic matter, inorganic N can be immobilized, especially when organic matter with a large C/N ratio is added to the soil.

Crop residues have a very low N (ca. 1%) and P content (ca. 0.1%). Given the lignin and polyphenol contents of crop residues, these residues play a more important role contributing to SOM build-up than as inorganic nutrient sources for plant growth.

3.2.2. Phosphorus

Numerous studies have reported higher extractable P levels in zero tillage than in tilled soil. This is 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. Accumulation of P at the surface of continuous zero tillage is commonly observed. If the surface soil dries out frequently during the growing season, a deeper placement of P in zero tillage can be an option. However, if mulch is present on the soil surface of zero tillage the surface soil is likely to be moister than conventionally tilled soils and there will probably be no need for deeper P placement.

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. Higher extractable K levels at the soil surface are observed when tillage intensity decreases. Increasing residue retention can also lead to an increased K concentration in the topsoil, although this effect is crop-dependent.

Most research has shown that tillage does not affect extractable Ca and Mg levels, especially where the cation exchange capacity (CEC) is primarily associated with clay particles. Also, the vertical Ca and Mg stratification seems unaffected by tillage and crop, but results are not conclusive.

3.2.4. Cation exchange capacity

The high organic matter contents at the soil surface, commonly observed under CA (see 3.1.1 Total soil organic carbon content) can increase the CEC of the topsoil. However, tillage practices and crop do not seem to have an effect on CEC. The retention of crop residues, however, can significantly increase the CEC in the 0–5 cm layer compared to soil from which the residue is removed.

3.2.5. Micronutrient cations and aluminum

Increasing supply of food crops with essential micronutrients might result in significant increases in their concentrations in edible plant products, contributing to consumer health. Micronutrient cations (Zn, Fe, Cu, and Mn) tend to be present in higher levels under zero tillage with residue retentions compared to conventional tillage. However, reports are not conclusive about this. Aluminum toxicity seems to be lower under zero tillage with residue retention, probably because of the formation of Al-organic complexes when water in the topsoil is available.

3.3. Acidity

Most studies have found that the pH of the topsoil was lower (more acidic) for zero tillage than for conventional tillage. There are some hypotheses for this acidification:

- The greater SOM accumulation in the topsoil with zero tillage led to acidity from decomposition
- 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.

However, there have been some contrasting results, where significantly higher pH was found in the topsoil of the permanent raised beds with full residue retention compared to conventional beds with residue retention.

3.4. Salinity/sodicity

As for the question of whether tillage practices influence the salinity of the soil, contrasting results have been found. In the highlands of Mexico, it was found that permanent raised bed planting is a technology that reduces soil sodicity under rainfed conditions. Furthermore, the Na concentration increased with decreasing amounts of residue retained on the permanent raised beds (Govaerts et al., 2007a). This can be important for saline areas. In contrast, it has been suggested in other research that tillage tends to reduce the potential for salt accumulation in the root zone.

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. Soil organisms respond to tillage-induced changes in the soil chemical/physical environment and they, in turn,

have an impact on soil chemical/physical conditions, i.e., soil structure, nutrient cycling, and organic matter decomposition. Interactions among different organisms can have either beneficial or harmful effects on crops.

Bacteria, fungi, and green algae are included in the microflora. The remaining groups of interest are referred to as soil fauna. The soil fauna are divided into three groups, 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 (Table 2).

4.1. Soil microfauna and -flora

Maintaining soil microbial biomass (SMB) and microflora activity and diversity is fundamental for sustainable agricultural management. Soil management influences soil micro-organisms 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.

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. It has some interesting characteristics:

- SMB responds to changes in soil management often before effects are measured in terms of organic C and N
- The SMB plays an important role in physical stabilization of aggregates
- 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

The rate of organic C input from plant biomass is generally considered the dominant factor controlling the amount of SMB in the soil. A continuous, uniform supply of C from crop residues serves as an energy source for micro-organisms. Residue retention can lead to significantly higher amounts of SMB-C and N in the topsoil layer compared to residue removal.

Residue management has more influence on SMB than tillage system. The significant changes are mostly confined to the topsoil layer. The influence of tillage practice on SMB-C and N is also mainly confined to the surface layers, at lower depths (5–10 cm and 10–15 cm) (Govaerts et al., 2007b), SMB-C and N are generally not significantly different.

The favorable 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.

The effects of several rotations are clear when the length of the fallow period is considered. Reducing the fallow increases SMB-C and N. Each tillage operation increases organic matter decomposition with a subsequent decrease in SOM.

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. It is not possible to determine the functional diversity of soil microbial communities based on community structure, largely because micro-organisms are often present in soil in resting or dormant stages. These dormant micro-organisms are overlooked in most measurements. Direct measurement of the functional diversity of soil microbial communities is likely to provide additional information on the functioning of soils.

The functional diversity is larger under zero tillage with residue retention than under conventional tillage. As long as residues are maintained, differences in the community-level physiological profile of the SMB are minimal between zero tillage and conventional tillage. When residues are removed, the functional diversity decreases in zero tillage (Govaerts et al., 2007b). Plant roots play an important role in shaping soil microbial communities by releasing a wide range of compounds that may differ between plants. This variation is known to select divergent bacterial communities. This indicates the importance of crop rotation for soil health.

Table 2. Soil fauna grouped according to size and habitat

| Name | Body width | Habitat | Examples |
|------------|------------|--|---|
| Microfauna | <0.2 mm | Water-filled pore space | Protozoa + nematodes |
| Mesofauna | 0.2–2 mm | Air-filled pore space of soil and litter | Microarthropods, springtails, small Oligochaeta |
| Macrofauna | >2 mm | Between soil aggregates | Termites, earthworms, large arthropods |

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. Management practices such as tillage, crop rotation, and residue management may have diverse effects on various soil enzymes. Enzyme activity generally decreases with soil depth. Therefore, differentiation among management practices is greater in the surface soil. Crop rotation and residue management can also affect soil enzyme activity. Reducing fallow seems to enhance enzyme activity of C and P cycling.

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.

4.1.4.1. Fungi and bacteria

Fungi are food for nematodes, mites and other, larger, soil organisms; but may also attack other soil organisms. Filamentous fungi are responsible for the decomposition of organic matter and participate in nutrient cycling. 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. Arbuscular mycorrhizae interact with pathogens and other rhizosphere inhabitants affecting plant health and nutrition.

It is often said that, at the micro-foodweb scale, zero tillage systems tend to be fungal-dominated whereas conventional tillage systems tend to be bacterial-dominated. However, this could depend on whether measurements are made near the soil surface or deeper in the soil profile, since the crop residues at the soil surface under zero tillage tend to be fungal-dominated. Disruption of the network of mycorrhizal hyphae, an important inoculum source when roots senesce, is a possible mechanism by which conventional tillage reduces root colonization by arbuscular mycorrhiza. Tillage also transports hyphae and colonized root fragments to the upper soil layer, decreasing the possibility of them being beneficial to the next crop.

When crop residues are retained, they serve as a continuous energy source for micro-organisms. Retaining crop residues on the surface increases microbial abundance because microbes encounter improved conditions for reproduction in the mulch cover. Reducing tillage also has an effect on certain bacteria, such as *Agrobacterium* spp. and *Pseudomonas* spp. Hence, it is not zero tillage per se that is responsible for the increased microflora, but rather the combination of zero tillage and residue retention.

4.1.4.2. Nematodes

It has been stated that under zero tillage, the crop residues are fungal dominated. A predominance of fungal feeding nematodes is found in the 0–5 cm layer in zero tillage. Reduced tillage leads to a significantly greater population of nematodes than conventional tillage. 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. The population of bacteria-feeders was significantly higher in conventional tillage than in zero tillage under residue retention (Yeates and Hughes, 1990). Crop rotation also seems to have an effect on the population of the total free-living nematode density.

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. Species that spend one or more stages of their life in the soil are most directly affected by tillage. When reduced tillage is combined with residue retention 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 tissue 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.

The most common root rot pathogens found on cereals under zero tillage systems are:

- Take-all, caused by *Gaeumannomyces graminis* (Sacc.) Arx & Olivier var. *tricitii* 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'Donnel & T. Aoki and other species belonging to the genus *Fusarium*
- Common root rot caused by *Bipolaris sorokiniana* (Sacc.) Shoem.

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 CA, and those that have done so have yielded conflicting conclusions. Residues on the soil surface result in a cooler and wetter surface soil. These conditions could be beneficial for the root infections by take-all, Pythium root rot and Rhizoctonia root rot. However, an increase in the prevalence of root rot is not always observed under zero tillage.

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 to infection.

As Fusarium foot and root rots survive in the straw, it could be possible that the disease would be more severe in direct-seeded than conventionally-seeded fields. An increase in the incidence of Fusarium root rot has been observed in some cases, but no direct relationship between increased root rot and yield was found.

Crop rotation may reduce pathogen carry-over on crop residues in the soil. In crop monoculture, the population of soil microbiota can build up for many years, leading to yield decline. A 2-year rotation cycle, including a 1-year break, can offer significant relief from pest pressures because of rotation-induced changes in the composition of the soil biota. Crop rotations, however, have to be economically viable to be adopted by farmers. For some diseases, like *Pythium* and *Rhizoctonia*, that have a wide host range, the use of crop rotation to manage root rots must include a plant-free break to be effective. This can mean expense, but no income, from that field, depending on the duration of the break. Pests can also adapt to crop rotation.

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. The changes in the organic matter content with zero tillage and residue retention can also favor growth of many other micro-organisms in the surface layer of the soil (0–10 cm). Therefore, zero tillage combined with crop residue retention may create an environment that is more antagonistic to pathogens due to competition and antibiosis effects.

Several fungal and bacterial species play a role in the biological control of root pathogens and, in general, the maintenance of soil health:

- Fluorescent *Pseudomonas* strains can suppress soil-borne plant pathogens used by a variety of mechanisms
- Many soil-borne *Actinomycetes* species produce bioactive metabolites that can be used in antibiotics
- Some *Fusarium* spp. are active biological control agents

In a study by Govaerts et al. (2006) zero tillage with rotation and residue retention enhanced water availability, soil structure, and nutrient availability more than conventional tillage and, as a result, gave higher yields. Zero tillage and crop residue increased the diversity of microbial life. Root diseases may have affected crop performance but the impact was less than other critical plant growth factors such as water availability or micro- and macronutrient status. In the long-term, zero tillage with crop residue retention creates conditions favorable for the development of antagonists and predators, and fosters new ecological stability (Govaerts et al., 2006). Thus, the potential exists for generally a higher suppression of pathogens in direct-seeded soils with crop residue retention.

Apart from strategic crop rotations and the increased biological control in CA systems, the use of soil fumigation has been proposed as a control measure for situations where soil-borne diseases may be a problem. Fumigation is economical only for certain high-value horticultural crops, such as strawberries.

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 pathogens. Future strategic research will need to concentrate on genotype by cropping system interactions.

Nematode densities range from 2×10^5 individuals m^{-2} in arid soil to more than 3×10^7 individuals m^{-2} in humid ecosystems. Yield losses due to nematodes can be expected under conventional cropping systems in sub-optimal irrigation and semi-arid conditions. A few plant parasitic nematodes are economically important, for instance *Pratylenchus thornei*, which can result in yield losses up to 40%. The presence of plant parasitic nematodes does not necessarily mean that crop yield will be adversely affected. It is possible that the population is below the damage threshold. Not all nematodes react equally to tillage and mulching. Under conditions of minimal soil disturbance, it is possible that populations of natural enemies of parasitic nematodes would be enhanced. The crop residues can also enhance the population of bacteria, providing food for the non-plant parasitic species. Hence, their number will increase under zero tillage with residue retention.

4.2. Soil meso- and macrofauna

From a functional point of view, soil macrofauna can be divided into two groups:

1. Litter transformers (large arthropods and soil mesofauna): Minor effect on soil structure. They fragment litter and deposit mainly organic fecal pellets.
2. Ecosystem engineers (mainly termites and earthworms): They ingest a mixture of organic matter and mineral soil and are responsible for a gradual introduction of dead organic materials into the soil. They strongly influence soil structure and aggregation.

4.2.1. Soil mesofauna

Soil microarthropods consist mainly of springtails and mites and form the major part of the soil mesofauna. Springtails are usually inhibited by tillage disturbances, although some studies have shown the opposite or no effect. Mites exhibit a wider range and more extreme responses to tillage than microbial groups, with moderate to extreme increases or decreases having been found. The different taxonomic groups of mites appear to respond differently to tillage disturbance, which explains some of the varied responses. The effect of tillage on microarthropod populations is caused in part by the physical disturbance of the soil by tillage. Some individuals may be killed by abrasion during tillage operations or by being trapped in soil clods after tillage inversion. 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.

4.2.2. Soil macrofauna

Large organisms appear to be especially sensitive to agro-ecosystem management. Species with high mobility and higher population growth potential will be less affected. Tillage, through direct physical disruption as well as habitat destruction, strongly reduces the populations of both litter transformers and ecosystem engineers. 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. Although crop rotations could theoretically be beneficial for soil macrofauna populations through greater biomass returns to the soil, concrete evidence on this is as yet inconclusive.

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. There are three kinds of earthworms:

- 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
- Endogeic: 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 the soils. The presence of all groups appears to be essential to maintain soil structure. In fact, unbalanced combinations of earthworms due to disturbances were found to reduce infiltration and cause severe erosion.

In general, earthworm abundance, diversity and activity were found to increase under CA compared to conventional tillage. 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). Earthworm castings promote the creation of stable organo-mineral complexes with reduced decomposition rates which favor soil macroaggregate stability if allowed to dry or age. However, when fresh casts are exposed to rainfall, they can be easily dispersed and contribute to soil erosion

and nutrient losses. Earthworms' activity is also reported to be related to increased infiltration in zero tillage soils through enhanced soil surface roughness and increased soil macroporosity, especially when populations are significant.

4.2.2.2. Termites and ants

It has been proposed that termites and ants are as important as earthworms in soil transformation. They are predominant in arid and semi-arid regions where earthworms are normally absent or scarce. In general, termites and ants increase infiltration by improving soil aggregation and porosity. Soil-feeding termites also form microaggregates either by passing soil material through their intestinal system and depositing it as fecal pellets or by mixing the soil with saliva using their mandibles. Ants change soil quality by increasing organic matter, sand, and silt and reducing clay, Ca, Mg, K, and Na concentrations, particularly in areas near and adjacent to ant hills and foraging paths.

Management options that favor ant and termite populations, such as residue mulch and reduced zero tillage, have been identified as key factors in improving the topsoil in agro-ecosystems, even in the degraded conditions of the Sahel. However, given the patchy and physically restricted distribution, it is not clear if ant and termite activity have any relevant effects at the field level. Moreover, their positive effect on soil structure can be counteracted by a negative effect on crop yield and residue retention through herbivorous activity.

4.2.2.3. Arthropods

Not all arthropods are litter transformers. However, most arthropods take part, at least partially, in organic matter incorporation through burrowing and food relocation thereby improving soil structure. Theoretically, arthropods are favored by CA conditions given litter presence on the soil surface constitutes a food source for many arthropods. Diversity of all arthropod species is usually higher in CA compared to conventional systems. Interestingly, an increased presence of predators compared to phytophagous species under zero tillage systems is found. This has strong implications for pest management.

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