Is conservation tillage suitable for organic farming?
A review

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Abstract
Conservation tillage covers a range of tillage practices, mostly non-inversion, which aim to conserve soil moisture and reduce soil erosion by leaving more than one-third of the soil surface covered by crop residues. Organic farmers are encouraged to adopt conservation tillage to preserve soil quality and fertility and to prevent soil degradation – mainly erosion and compaction. The potential advantages of conservation tillage in organic farming are reduced erosion, greater macroporosity in the soil surface due to larger number of earthworms, more microbial activity and carbon storage, less run-off and leaching of nutrients, reduced fuel use and faster tillage. The disadvantages of conservation tillage in organic farming are greater pressure from grass weeds, less suitable than ploughing for poorly drained, unstable soils or high rainfall areas, restricted N availability and restricted crop choice. The success of conservation tillage in organic farming hinges on the choice of crop rotation to ensure weed and disease control and nitrogen availability. Rotation of tillage depth according to crop type, in conjunction with compaction control measures is also required. A high standard of management is required, tailored to local soil and site conditions. Innovative approaches for the application of conservation tillage, such as perennial mulches, mechanical control of cover crops, rotational tillage and controlled traffic, require further practical assessment.

Keywords: Organic farming, conservation tillage, weeds, crop nutrition, soil structure

Introduction
For this review, tillage systems may be separated into two types (Köller, 2003), conservation tillage and conventional tillage. Conservation tillage covers a range of practices which conserve soil moisture and reduce soil erosion by maintaining a minimum of 30% of the soil surface covered by residue after drilling. Generally, conservation tillage includes a shallow working depth without soil inversion, i.e. no tillage or reduced or shallow tillage with tine or discs. Shallow ploughing, to no more than 10 cm, should be included in conservation tillage because burial of crop residues is usually incomplete. Conventional systems of tillage leave less than 30% of crop residues – and often none – on the soil surface after crop establishment. Conventional tillage is invariably deeper (20–35 cm) with inversion of the soil by mouldboard plough, disc plough or spading machine.

Conservation tillage leaves an organic mulch at the soil surface, which reduces run-off, increases the surface soil organic matter (SOM) promoting greater aggregate stability which restricts soil erosion (Franzluebbers, 2002a). Other beneficial aspects of conservation tillage are preservation of soil moisture and increase of soil biodiversity (Holland, 2004).

Reducing the intensity of soil tillage decreases energy consumption and the emission of carbon dioxide, while increasing carbon sequestration (Holland, 2004). Reducing the intensity of tillage increases the sustainability of tillage systems by speeding up crop establishment and reducing labour demand (Davies & Finney, 2002). Organic production of field crops generally consumes up to 20% less energy than non-organic agriculture (Williams et al., 2006). However, environmental burdens, such as global warming potential or eutrophication, can be greater under organic farming (Williams et al., 2006). Thus conservation tillage may improve the environmental and economic performance of organic farming.
The International Federation of Organic Agriculture Movements standards (IFOAM, 2002) recommend that organic farmers ‘should minimize loss of topsoil through minimal tillage, contour ploughing, crop selection, maintenance of soil plant cover and other management practices that conserve soil’ and ‘should take measures to prevent erosion, compaction, salinization, and other forms of soil degradation’. Effectively, organic farmers are encouraged to adopt conservation tillage, especially if they are located in areas susceptible to erosion. Conservation tillage offers benefits that could improve the soil fertility, soil quality and the environmental impact of organic crop production. However, Koepke (2003) reported that organic farmers generally use the mouldboard plough, working to a greater depth (Munro et al., 2002) or to a lesser depth (Watson et al., 2002) than in conventional agriculture. The relevance of conservation tillage should be assessed in organic crop production. Thus, the purpose of this paper is to highlight the advantages of, and limits to the adoption of conservation tillage in organic farming in terms of the main functions of tillage with emphasis on soil and agronomic aspects rather than economics.

Mouldboard ploughing is a traditional cultural operation, which incorporates surface organic residues, stimulates mineralization and thereby aids crop nutrition. Tillage management plays a key role in SOM turnover. Soils under organic farming receive frequent organic matter inputs as manures and organic fertilizers (Shepherd et al., 2002). As organic fertilizers are expensive, generally fewer nutrients are supplied in organic farming (David et al., 2005). Thus, the nutrient contributions from SOM are of greater importance in organic farming (Stockdale et al., 2002). Nitrogen (N) is supplied by the combined use of N fixed in legumes in the rotation and organic manures. Tillage incorporates and distributes this organic matter through the topsoil providing conditions suitable for mineralizing nutrients, particularly N. Tillage also facilitates seedbed preparation, improving conditions for rooting and nutrient uptake (Koepke, 2003). Soil tillage, especially conventional ploughing, is crucial for the control of weeds in organic farming (Trewavas, 2004). Weeds are one of the most important factors limiting organic crop production (Bond & Grundy, 2001). Sadowski & Tyburski (2000) and Hyvönen et al. (2003) found a greater density and diversity of weed species in organic fields than in conventional production.

According to these characteristics of organic farming, three main aspects will be emphasized in this review to determine the suitability of conservation tillage: (1) the preservation of the biological, chemical and physical components of soil fertility and quality; (2) the preservation of soil functions, such as mineralization, support of root growth, soil water drainage and storage; and (3) the role of soil management in weed, disease and pest control. We focus mainly on organic arable systems in western Europe.

**Preservation of soil quality and fertility**

**Residue distribution within the soil profile**

The different types of tillage system involve different stratification of the soil layers (Figure 1a–c). The soil is divided into three layers: the surface, the topsoil and the subsoil layers. The surface layer corresponds to the seedbed. The topsoil is historically the plough depth (20–40 cm). The subsoil is the undisturbed part of the soil profile below the topsoil. The tilled layer varying from 5 to 40 cm contains the crop residues. Less crop residue is left on the soil surface with reduced or shallow tillage than with no tillage. The reduced tillage method leaving least residues at the surface is shallow ploughing. Furthermore, disc harrows incorporate more crop residues than chisel tines. The main impacts of the different tillage systems on seedbed quality are due to changes in the thickness, extent of soil inversion and extent of mixing of crop residue caused by the implement. The extent of residue incorporation is influenced by the degree of disintegration of the residues, e.g. straw length.

![Figure 1](image-url)
Chemical and biological properties

The quantity of SOM in the whole topsoil varies due to the interacting influences of climate, topography, soil type and crop management history (fertilizer use, tillage, rotation and time) (Kay & VandenBygaart, 2002). Thus, in conservation tillage, SOM and microbiological activity are stratified in the soil profile, according to the burial depth of crop residues and manures (Needelman et al., 1999; Franzluebbers, 2002a). However, several authors have shown that there is no significant increase in the overall mass of soil organic carbon (C) (Table 2) or of soil microbial biomass (Table 1) in the whole topsoil in different tillage systems. SOM, organic C and soil microbial biomass increase in the tilled layer and are unchanged or decreased in the untilled layer below conservation tillage compared with conventional tillage (Table 1). Similarly, total N, organic N and mineralizable N, phosphorus (P) and potassium (K) follow the same pattern as C and SOM, with greater concentration in the soil surface layer (tilled layer) in conservation tillage, but without a significant increase in the whole topsoil. In a pan-European study, Ball et al. (1998) concluded that additional carbon fixation by the storage of organic matter and oxidation of atmospheric methane was very limited under reduced tillage and likely to last for a short period only. The authors also considered that soil nitrate was vulnerable to loss by denitrification, particularly in wet, fine-textured soils. However, less N is likely to be lost as a result of run-off and leaching than under conventional tillage. According to Sisti et al. (2004), the combined action of conservation tillage and the input of fresh organic matter as leguminous residues increased the soil C and, in the long term, improved the mineral N supply to crops.

In a long-term study, Fließbach & Mäder (2000) and Pfiffner & Mäder (1997) showed that soil microbial biomass and its activity increased in organic farming compared with conventional management. Comparing properties of organically and conventionally managed soils of 28 sites on commercial farms, Munro et al. (2002) concluded that soils in organic systems contained more organic matter and total N than conventionally farmed soils. Frequent input of fresh organic matter, with no pesticide use, is the most probable cause of the increasing percentage of organic matter and biological activity found in organic systems. However, according to Shepherd et al. (2002) (cited in Stockdale et al. (2002)), few differences in organic matter content exist between organically and conventionally managed pastures in the UK. The main difference in SOM was found between conventional and organic arable land, where fresh organic matter was applied more frequently in organic systems. Moreover, no consistent difference was found in the quantity of nutrient reserves held in organic forms, between organically and conventionally managed soils (Stockdale et al., 2002).

Table 1 Effects of tillage systems on SOM, organic C and N, soil microbial biomass

<table>
<thead>
<tr>
<th>Soil components</th>
<th>Comparison of conservation tillage relative to conventional tillage</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic matter</td>
<td>More in the tilled layer</td>
<td>Andrade et al. (2003)</td>
</tr>
<tr>
<td></td>
<td>Similar in the untilled layer</td>
<td>Kay &amp; VandenBygaart (2002)</td>
</tr>
<tr>
<td></td>
<td>Similar in the untilled layer</td>
<td>Balesdent et al. (2000) and Deen &amp; Kataki (2003)</td>
</tr>
<tr>
<td></td>
<td>Similar throughout the topsoil</td>
<td>Anken et al. (2004)</td>
</tr>
<tr>
<td>Total carbon</td>
<td>More in the 0–5 cm layer but similar in the 5–20 cm layer under no tillage</td>
<td>Six et al. (1999)</td>
</tr>
<tr>
<td>Microbial biomass</td>
<td>More in the tilled layer</td>
<td>Stockfisch et al. (1999) and Kay &amp; VandenBygaart (2002)</td>
</tr>
<tr>
<td></td>
<td>Similar in the untilled layer</td>
<td>Aon et al. (2001) and Kay &amp; VandenBygaart (2002)</td>
</tr>
<tr>
<td></td>
<td>More active microbial biomass in the 0–5 cm layer under no tillage</td>
<td>Alvarez &amp; Alvarez (2000)</td>
</tr>
<tr>
<td>Microbial diversity</td>
<td>More fungi than bacteria in crop residue at soil surface</td>
<td>Kladivko (2001)</td>
</tr>
<tr>
<td>Macro-organisms</td>
<td>Specific effects:</td>
<td>Rasmussen (1999)</td>
</tr>
<tr>
<td></td>
<td>More endogeic species during a short period</td>
<td>Chan (2001)</td>
</tr>
<tr>
<td></td>
<td>Effects on quantity:</td>
<td>Chan (2001)</td>
</tr>
<tr>
<td></td>
<td>More Earthworms, nematodes</td>
<td>Chan (2001)</td>
</tr>
<tr>
<td></td>
<td>Depends on tillage depth and intensity (no tillage &gt; reduced tillage) and also on time and soil type</td>
<td>Chan (2001)</td>
</tr>
</tbody>
</table>
quantity and quality of crop residues and animal manures will determine the amount of N which becomes available (Berry et al., 2002).

Hence, although we expect that the combined effects of organic farming and conservation tillage could improve the SOM content and consequently the soil nutrient reserves in organic stockless system, further research on the combined effects is required.

The number of earthworms and their activity increase in conservation compared with conventional tillage (Table 1). Ploughing disrupts earthworm soil habitats, especially deep burrowing species (anecic), and exposes earthworms to predation and desiccation (Holland, 2004). In the same way, the increase of fresh organic matter in organic farming is an additional resource stimulating trophic and burrowing activity of earthworms (Gerhardt, 1997; Glover et al., 2000; Shepherd et al., 2000). Thus, both organic farming and conservation tillage improve the activity of earthworms. This is especially important in arable systems where generally earthworm activity is much reduced compared with grassland.

Physical properties

Aggregate stability

One of the main objectives of conservation tillage is to reduce soil erosion (Holland, 2004). Soil organic matter, concentrated near the soil surface with conservation tillage (Table 1), and especially labile organic matter (Ball et al., 2005), encourages microbial activity leading to increased soil aggregate stability (Table 3) and improved soil structure. In the same way, fungal hyphae, more abundant in the surface layer in conservation tillage (Table 1), play an important role in aggregating and stabilizing soil structure. Also, with no tillage, crop residues at the soil surface prevent surface crusting (Azooz & Arshad, 1996). This improved aggregate stability tends to enhance infiltration rate which in turn results in less run-off containing dissolved nutrients and adsorbed P.

Organic matter plays an important role in the maintenance of soil structure. Shepherd et al. (2002) assessed soil structure in over 90 arable fields managed under organic and conventional systems. They found that the potential for structural improvement in soils under organic production was greater than in conventional soils due to the greater biological and earthworm activity enhanced by regular application of organic matter, improving aggregate stability and biological porosity. Helfrich (2003) found that increasing the duration of the ley phase in an organic ley-arable rotation increased aggregate stability. Voorhees & Lindstrom (1984) (cited in Munkholm et al., 2001) considered that a period of about 3–5 years from adoption of conservation tillage is required to improve the friability of the surface layer of fine-to-medium-textured soils.

Compaction

Compaction can result in deterioration of both topsoil and subsoil structures, mainly caused by vehicle traffic, soil tillage system (implement use and depth of work) and grazing intensity (Hamza & Anderson, 2005). Here we distinguish three kinds of compaction: (1) short-term compaction directly related to the bulk density of the plough layer, which can be

Table 2 Effects of tillage systems on N, P and K

<table>
<thead>
<tr>
<th>Soil components</th>
<th>Comparison conservation vs. conventional tillage</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total nitrogen</td>
<td>More in the tilled layer with shallow tillage</td>
<td>Stockfisch et al. (1999)</td>
</tr>
<tr>
<td></td>
<td>Similar in the untilled layer</td>
<td></td>
</tr>
<tr>
<td>Organic nitrogen</td>
<td>More in the tilled layer</td>
<td>Balesdent et al. (2000)</td>
</tr>
<tr>
<td></td>
<td>Similar in the untilled layer</td>
<td>Balesdent et al. (2000) and Aon et al. (2001)</td>
</tr>
<tr>
<td>Mineralizable nitrogen</td>
<td>More in the tilled layer</td>
<td>Six et al. (1999) and Balesdent et al. (2000)</td>
</tr>
<tr>
<td></td>
<td>Similar in the whole topsoil</td>
<td>Six et al. (1999)</td>
</tr>
<tr>
<td>Mineralized nitrogen</td>
<td>More in the tilled layer</td>
<td>Kandeler et al. (1998) and Young &amp; Ritz (2000)</td>
</tr>
<tr>
<td></td>
<td>Similar in the untilled layer</td>
<td></td>
</tr>
<tr>
<td></td>
<td>More in the tilled layer after 10 years</td>
<td>Ahl et al. (1998)</td>
</tr>
<tr>
<td></td>
<td>Less in the whole topsoil after 10 years</td>
<td></td>
</tr>
<tr>
<td></td>
<td>More in the whole topsoil in long term</td>
<td>Andrade et al. (2003)</td>
</tr>
<tr>
<td></td>
<td>Less in the whole topsoil in short term</td>
<td></td>
</tr>
<tr>
<td>Available phosphorus</td>
<td>More in the tilled layer</td>
<td>Rasmussen (1999)</td>
</tr>
<tr>
<td></td>
<td>Similar in the untilled layer</td>
<td></td>
</tr>
<tr>
<td>Available potassium</td>
<td>More in the tilled layer under shallow tillage</td>
<td>Rasmussen (1999)</td>
</tr>
<tr>
<td></td>
<td>Similar in the untilled layer</td>
<td></td>
</tr>
</tbody>
</table>

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reversed by deeper tillage; (2) long-term topsoil compaction resulting from sustained physical degradation and (3) long-term subsoil compaction (Arvidsson & Hakansson, 1996). Tillage needs to be managed to prevent long-term topsoil and subsoil compaction problems.

Conservation tillage improves surface soil structure and can reduce compactibility (Ball et al., 1996) due to the concentration of decomposing crop residues (Figure 2). However, Munkholm et al. (2003) studying a weak sandy loam soil in a moist and cool climate, observed deterioration of the structure in the seedbed below the tilled layer, especially with single-disc direct drilling. This may have been due to the weak structure of soils of this texture. The modification of soil structure after the adoption of conservation tillage depends on structure-forming activity, itself related to clay content and clay mineralogy (Alakukku, 1998), weather conditions, organic matter content and biological activity. Actually, many studies in several soil and climate conditions have demonstrated additional compaction in the untilled layer of conservation tillage, with a decrease of the total porosity (Table 3). Soil compaction is a crucial problem, although consolidation of an undisturbed soil may give the benefit of a firm, level surface for traffic with no adverse effects on cropping provided that coarse pore continuity is enhanced (Davies & Finney, 2002).

According to Rasmussen (1999) compaction of the untilled layer may be counterbalanced by an increase of biological macroporosity in conservation tillage (Table 3). During the transition period to conservation tillage, Kay & VandenBygaart (2002) observed a decrease in the volume of the 30–100-μm pores in the 0–20-cm depth accounting for much of the decrease of total porosity, whereas biopores 100–500 μm may have increased at a depth of 10–30 cm.
that after equal compactive effort applied to a clay loam and a silt loam, the soils compacted more under shallow tillage (10 cm depth) than with ploughing (20 cm depth). Nevertheless, in both treatments, after 4–5 years, no residual effects of the topsoil compaction on penetration resistance and bulk density were detected. According to the authors, the soils were originally well drained and earthworm burrows were present in all treatments. However, subsoil compaction (20–55 cm) persisted for the duration of the experiment.

In organic farming, the topsoil is more dense under conservation tillage than conventional (Munkholm et al., 2001; Kouwenhoven et al., 2002). Moreover, subsoil compaction remaining from earlier soil management operations (Schjonning et al., 2002) can persist after transition from conventional to conservation tillage (Munkholm et al., 2001). However, in the experiment detailed by Munkholm et al. (2001), the duration of the measurement period during the transition to conservation tillage was too short to identify potential differences between organic and conventional farming.

Soil type influences suitability for conservation tillage, particularly no tillage, by influencing soil structure, mainly as a result of compaction. Thus, soils containing large percentages of silt and fine sand tend to have weak unstable structure, and a high content of non-expanding clay minerals tends to limit structural improvement by swelling and shrinking (Carter, 1994). This situation is worse when the soil is wet due to poor drainage and high rainfall. Such soils are likely to be less suited to organic farming because of the tendency to overcompact leading to poorer growth of legumes, slower mineralization of crop residues and greater losses of mineralized N than in drier, coarser textured soils (DEFRA, 2006). Although schemes of soil suitability for reduced or no tillage have been produced, Davies & Finney (2002) concluded that the flexibility of reduced tillage, particularly in depth of working, means that some degree of reduction of tillage input is possible in almost all farming situations, including root cropping. Carter (1994) also suggested that tillage timing can be changed by use of crops which allow establishment at drier times of year, by use of crops with less need for tillage and by use of rotational cropping. Cover crops can also be chosen such that the timing of tillage for their establishment is when the erosion hazard is low.

Alleviation of compaction. Hamza & Anderson (2005) reviewed technical solutions to prevent, mitigate or loosen compacted soil, such as controlled traffic, the combination of soil management practices to reduce the number of passes and loosening compacted soil by subsoiling or deep ripping. Subsoiling and conservation tillage are compatible provided the deep loosening causes minimal inversion and consequently organic material stays near the soil surface. However, the subsoiling requirement for powerful tractors does not favour any reduction of cultivations costs. The adaptation of crop management, including the addition of organic matter which stabilizes soil aggregates and the insertion in the rotation of grain or fodder crops and plants with strong tap roots (e.g. winter oil seed rape), could break up compacted soils (Hamza & Anderson, 2005). The preservation of subsoil structure is particularly important in organically managed soils where mechanical weeding can compact a substantial area of subsoil (Ball, 2006). Perennial crops may be required in areas where subsoils are compact or waterlogged. Earthworm activity helps to alleviate subsoil compaction. However, under no tillage severe subsoil compaction may be difficult to alleviate through the cumulative effects of earthworm activity and effects of weather (Chan et al., 2002; Van den Akker et al., 2003). For example, Alakukku (1996) found that the effects of subsoil compaction under conservation tillage were still measurable 9 years after the compaction event in organic clay-loam soils. The capacity of earthworms to penetrate a plough pan is a key element. According to Kemper et al. (1988) (cited in Brussaard & Van Faassen 1994), *Lumbricus terrestris* (anecic species) does not penetrate soil with a bulk density >1.6 Mg m$^{-3}$. In the same way, Kretzschmar (1991) found that cast production was governed by the degree of compaction, with two threshold limits. These were a lower limit below which few casts are produced because there was no need to dig, and an upper limit beyond which the earthworms were constrained mechanically. Nevertheless, more research on the ability of earthworms to penetrate a compacted area under field conditions is required.

Rotation is important in helping restore soil structure. It has long been recognized that a period under grass or under clover improves soil structure (Oades, 1984; Haynes, 1999). In mixed organic farming systems (cereals and fodder crops), the introduction of a perennial forage legume improved soil structure because of well-developed root systems and less grazing in the forage fields. Radford et al. (2001) compared several treatments of ploughing and reduced tillage in dry and wet conditions to restore a compacted Vertisol. The treatment with a lucerne ley plus Gatton panic (*Panicum maximum*, a subtropical grass) for 3 years (cut 10 times and returned to the soil), followed by reduced tillage in dry conditions was best for restoring and improving soil structure. In this experiment, crop and pasture roots improved soil structure by creating wet–dry cycles. However, the authors highlight two main limits of this system: the compaction due to animal grazing and/or the cutter used in wet soil conditions, and poor economic returns. Thus, although organic grain farmers can improve soil structure before the arable phase by growing a ley, for instance, 3 years dried lucerne (Ball et al., 2005), there needs to be a market for the produce and grazing and/or cutting should be confined to dry conditions.
We recommend that, before starting to use conservation tillage, the soil profile is examined to detect any compact layers from the previous cropping system and that these are alleviated. We would also recommend that compaction-reducing measures, such as low ground pressure tyres and use of low tyre inflation pressures, be considered to improve the sustainability of conservation tillage. The viability of conservation tillage would be enhanced considerably by the use of wide-span gantries and permanent wheelways (Davies & Finney, 2002).

**Soil function**

**Soil mineralization**

Nitrogen supply often limits yields in organic farming and increasing the efficiency of organic farming is possible mainly by adjusting the N status (Williams et al., 2006). The release of available N for crop uptake depends on the mineralization–immobilization balance in organic matter turnover. The amount and timing of mineralization is favoured by several factors including soil moisture, aeration and temperature, and by the nature and accessibility of organic materials to the microbial biomass (Berry et al., 2002). Fresh organic matter input with a high labile SOM fraction improves the mineralization rate by increasing microbial activity.

Mineralization of the SOM is affected by the tillage system. Conventional tillage disrupts aggregates, exposes the SOM, and increases its decay rate. This phenomenon is due to an increase in the aeration and the temperature of the tilled layer, to the incorporation and mixing of C inputs improving microbial activity, and the release of previously physically protected SOM (Balesdent et al., 2000). The timing and intensity of conventional tillage events affect net mineralization. For instance, more N is released when tillage coincides with periods of high soil temperature and/or moderate soil moisture (Pekrun et al., 2003).

Thus, conventional tillage increases net mineralization of SOM compared with conservation tillage. In conservation tillage, especially no tillage, there is a greater pool of soil labile N from microbial activity in the surface layer. However, this pool has a slower turnover rate caused by the decrease of the decay rate of SOM (Balesdent et al., 2000; Kay & VandenBygaart, 2002). Pekrun et al. (2003) indicated that net N immobilization can occur with slow SOM turnover during the transition period from conventional to conservation tillage. Moreover, soil compaction also affects the mineralization of soil C and N (Hamza & Anderson, 2005). Thus, topsoil compaction in conservation tillage alters the habitat of soil micro-organisms and consequently their activity by modifying the content and diffusion of soil gases (CO₂ and O₂) and soil water (Ball et al., 2005). For instance, more denitrification can occur (Ball et al., 1999), making less N available for crops. As many of the benefits of conservation or no tillage depend on enhanced microbial activity, Ball et al. (1998) suggested that these techniques were best suited, for general use, in semi-humid or drier regions.

Due to these effects of conservation tillage on SOM turnover, although soils managed by conservation tillage contain similar overall amounts of mineralizable N to conventionally tilled soils, in the short term less mineralized N is found than in ploughed soils (Table 3).

In tillage experiments on organic farms, Koepke (2003) and Vakali et al. (2002) found less mineralized nitrogen in shallow tillage than with ploughing. Although SOM content can increase in organic farming, the lack of mineral N input may slow down the supply of available N to crops. As conservation tillage and organic farming increase earthworm numbers, their activity in physically breaking down organic residues thereby encouraging microbial activity could lead to improved N release.

**N supply and organic matter incorporation.** Significant and frequent organic matter inputs on organic farms could be manipulated to regulate mineralization, particularly in stockless rotations. Fresh organic matter, as farmyard manure and green manure, is easily available to the microbial biomass because of the high content of labile organic matter fractions. Incorporation of farmyard or green manure with N rich, low C/N residues leads to rapid mineralization and slow immobilization (Watson et al., 2002). Thus, this fresh organic matter could be incorporated to release nitrogen at critical stages of crop nutrition in conservation tillage. However, the timing and conditions of incorporation must be carefully controlled. For instance, in organic rotations, environmental conditions at the time of ploughing of the clover leys are important in regulating the release of the accumulated biologically fixed N. Ploughing in warm conditions can result in significant losses of N as leachates (Djurhuus & Olsen, 1997) or as nitrous oxide (Ball et al., 2006). However, replacement of ploughing by conservation tillage at the end of the ley phase may also have negative consequences for uptake of mineralized N by subsequent arable crops, caused by slow mineralization. Tillage of the ley phase warrants further exploration to maximize the efficiency of release and uptake of fixed N.

**N supply and crop rotation.** According to a detailed review by Watson et al. (2002), crop N supply in organic farming can be managed with crop rotations. To make best use of the large quantity of N released after incorporation of leys, crops with a high N demand, such as winter wheat or potatoes, should be grown early in the arable phase. Crops with a lower N requirement, such as peas, should be grown later in the arable phase. The use of crops with a long period of N uptake, such as potatoes and spring barley, make good use of the slow but prolonged release of available N (Berry
et al., 2002). Other means to improve resource use are growing legumes and crops with different rooting depths, crop variety mixtures, intercropping (intercrop combination of cereals and legumes). These innovative uses of crops lead to rotations whose design needs to include other agronomic aspects, such as disease and weed control. Conservation tillage is normally used with non-root crops, although potatoes can be grown successfully using direct planting into stubble with tillage used only for the creation of ridges (Ekeberg & Riley, 1996). Another aspect to be aware of is inhibition of mid-season mineralization of N caused by mechanical weed control (Owen et al., 2006).

Emergence and root growth

The impact of seedbed quality on crop emergence, for a given climate, depends on conditions of soil structure (seed–soil contact, depth and regularity of the seedbed), temperature, moisture of the surface layer, and presence or absence of crop residues at the soil surface (Caneill & Bodet, 1994). Conservation tillage decreases temperature in the soil surface layer (Guerif, 1994) and increases residues; thus, it could impede crop emergence. Short-term topsoil compaction may delay crop emergence, for example, sugar beet (Gemtos & Lellis, 1997), maize (Radford et al., 2001) or wheat (Radford et al., 2001) and ultimately decrease yields because of rooting problems (Whalley et al., 1995). This delay in crop emergence could be a problem in organic farming where weed competition is a strong limiting factor.

Transition to conservation tillage on a clay soil (55% clay) reduced rooting density at 15–25-cm depth in barley and oats (Pietola, 2005). In this study, root growth was still negatively affected by long-term topsoil compaction 5 years after initiation of conservation tillage, although crop yields were not. Rasmussen (1999) found that root growth was promoted by the presence of cracks, worm channels and other large pores in the soil. Conservation tillage decreases total macroporosity, but increases worm channels. Consequently, root development in conservation tillage depends on the biological macropores in soil to compensate for the absence of the mechanical macropores introduced by the plough (Whalley et al., 1995).

Soil water storage and infiltration

The increased C content in the soil surface layer under conservation tillage increases the water storage capacity (Lampurlanés, 2000) and consequently the water retention (Richard et al., 2001; Franzluebbers, 2002b). Soil water infiltration can vary greatly in conservation tillage, according to total porosity and pore size distribution (Rasmussen, 1999). In conservation tillage, residue cover at the soil surface increased the continuity of biological pores (Francis & Fraser, 1998; Hangen et al., 2002; Kay & VandenBygaart, 2002) and microporosity (Arshad et al., 1999; Kay & VandenBygaart, 2002). These conclusions are confirmed by several authors who found that the increased earthworm population under conservation tillage favoured water flow and infiltration (Francis & Fraser, 1998; Hangen et al., 2002). However, where wet conditions coupled with traffic have destroyed the macropore system, infiltration rates will be much slower than in ploughed soils.

Weed, disease and pest control

Weed pressures

Tillage influences weed populations by the combined effects of mechanical destruction of weed seedlings and by changing the vertical distribution of weed seeds in the soil. Tillage also acts indirectly on weed populations, through the changes in soil conditions, influencing weed dormancy, germination and growth.

Weed seeds are more uniformly distributed in the topsoil with conventional tillage, but are mainly located in the first few centimetres of soil under conservation tillage (Ghersa & Martinez-Ghersa, 2000; Kouwenhoven, 2000; El Titi, 2003; Moonen & Barberi, 2004; Mohler et al., 2005). Perennial and annual grasses are more highly represented in conservation tillage than in conventional (Kouwenhoven, 2000; Torresen et al., 2003; Moonen & Barberi, 2004), and the control of grass weeds is critical to the success of reduced tillage (Davies & Finney, 2002). Conservation tillage modifies the micro-topography, the light, water and temperature conditions in the soil surface layer (Ghersa & Martinez-Ghersa, 2000), which in turn influences the emergence of weed seeds according to their type and the climatic conditions (Debaeke & Orlando, 1994). No tillage tends to modify the 0–5-cm soil layer, by decreasing aggregate size and increasing the total porosity. These modifications can also influence weed emergence. For instance, in conservation tillage, the seed–soil contact, modified by interference with crop residues, could be less advantageous for germination and emergence of small-seeded weeds (Bond & Grundy, 2001). Nevertheless, a greater proportion of the seed bank germinates in conservation tillage (Hakansson et al., 1998; Kouwenhoven, 2000; Kouwenhoven et al., 2002) favouring the emergence of grass weeds and other species with a large rate of seed production (El Titi, 2003). For dicotyledonous weeds, the impact of tillage systems depends on the species (Kouwenhoven, 2000; Moonen & Barberi, 2004). For instance, conventional tillage tends to increase some annual dicotyledons, such as Chenopodium sp. and Papaver rhoeas, when their persistent seeds are brought back to the surface by ploughing (Ghersa & Martinez-Ghersa, 2000; Locke et al., 2002). With conservation tillage, there is no sudden and brief seed exposure to light and change of soil temperature as occurs when the top-soil is inverted. Thus, the germination of older and deeper
located persistent weed seeds is slowed down (El Titi, 2003; Moonen & Barberi, 2004).

Weeds with creeping roots or rhizomes are favoured by the absence of tillage (Torresen et al., 2003). However, conservation tillage with tines or discs can also assist their development by disrupting and dispersing their rhizomes, especially Agropyrum repens. In the same way, Elymus repens, favoured by conservation tillage, could present a major problem in organic farming (Kouwenhoven et al., 2002).

The unfavourable changes in weed seed bank and weed emergence often deter organic farmers from adopting conservation tillage (Rodriguez, 1999; Shepherd et al., 2000; Kouwenhoven et al., 2002). In a review, Van Elsen (2000) described the effects of the conversion from conventional to organic farming on weeds. The prohibition of inorganic N fertilizers decreases the nitrophilous weed species (e.g. Galium aparine) and increases leguminous weed species. Perennial crops established traditionally in organic crop rotations favour fewer long-lived annual weeds but more perennial ones (e.g. Rumex crispus and Rumex obtusifolius). Moreover, organic fields contain more perennial dicotyledons, such as Cirsium arvense (Koepeke, 2003).

Kouwenhoven et al. (2002) suggested that shallow ploughing (12–20 cm) was the best reduced tillage in shrink/swell soils for controlling weeds, especially perennials. In a long-term experiment in Römmersheim in Germany, Vakali et al. (2002) compared three tillage systems in organic farming: mouldboard ploughing, ‘two-layer ploughing’ (i.e. deep loosening without soil inversion and shallow tillage) and shallow tillage with a cultivator. As expected, these authors found that dry matter production of weeds was smaller in ploughed fields compared with those treated with the tine cultivator. However, they found no significant difference in yield between the ploughed treatment and the ‘two-layer ploughed’ treatment (Koepeke, 2003). This result suggests that soil inversion is not essential to prevent weed development. Also, important for weed growth is the depth and efficiency of the seedbed tillage following the ploughing.

**Weed control**

When conservation tillage is adopted in organic farming, weed management requires replacement of ploughing by other techniques. Several agricultural techniques can be used to control weeds in organic farming under conservation tillage. All these techniques contribute to improve crop competition against weed development (Barberi & Paolini, 2000; Rasmussen, 2004). The efficiency of the cultural operations depends on several factors. These include the initial weed seed bank (Rasmussen, 2004), soil and weather conditions which influence the efficacy of direct mechanical weed control, and stage of crop development.

**Stale or false seedbeds.** Stale/false seedbeds are one of the most useful preventative methods for organic weed control systems by managing weed development before sowing (Bond & Grundy, 2001). The seedbeds are prepared several days before sowing to encourage weed seeds to germinate and emerge. Then, weeds are eliminated by harrowing or flaming. Many parameters must be controlled with stale seedbeds: the rate and extent of weed emergence, the working depth of the implement used and the soil and climatic conditions (Bond & Grundy, 2001). For instance, stale seedbeds will be effective before spring crops when high soil temperatures and moist soil conditions enhance weed germination, but are of no value in very dry conditions before autumn-sown crops. Indeed, stale seedbeds can result in adverse effects if the working depth is too deep or soil temperature falls, resulting in delays in the emergence of weeds leading to competition with the crop.

**Mechanical weed control.** In shallow conservation tillage unlike no tillage, the partial burial of crop residues allows the use of direct mechanical weed control during the crop cycle, provided that crop residues on the soil surface do not obstruct the implements. After crop establishment, mechanical weed control is the most useful technique in organic farming irrespective of tillage system. The main methods used are hoeing, harrowing, finger weeding and brush weeding (Bond & Grundy, 2001). Other methods developed in organic farming are mowing, cutting, strimming and flaming. The effectiveness of all of these techniques depends on soil type and conditions, mainly soil water content, weed species and growth stage of crop and weeds (Table 4). Anken & Irla (2000) compared chemical and mechanical weed control with powered rotary harrows or no tillage with disc implements. Slightly lower yields (5–10% reductions) were obtained with mechanical weed control. However, there was no information of their effectiveness over the transition period to conservation tillage. For perennial grass weeds in organic farming systems, cutting to prevent further seeding gives some control of C. arvense in conservation tillage (Table 4). However, this method is not effective on all perennial weeds, e.g. Rumex spp.

The intensive use of mechanical weed control increases crop damage. According to Rasmussen et al. (2000), in a wheat field with high weed pressure, cereals should be sown in wider than normal rows to enable post-emergence hoeing. This method is appropriate for winter cereals where post-emergence harrowing can damage the crop if soil is too wet. Post-emergence harrowing should be used at early weed growth stage. If the weeds are too large, increasing implement working depth to maintain effectiveness can increase the risk of damaging the root system of crops (Hatcher & Melander, 2003). Finally, the repeated traffic associated with mechanical weeding can increase compaction (David & Gautronneau, 2002). To avoid soil compaction, mechanical
weed control must be performed in good soil conditions, i.e. at appropriate moisture and, ideally, with light vehicles running on dedicated wheel tracks (bed system).

**Effect of crop rotation.** A diverse crop rotation introduces different crop growth periods, competitive characteristics and management practices. The regeneration niche of different weed species can be disrupted and increases in some weed species prevented (Liebman & Davis, 2000). Choice of crop sequence offers opportunities to disrupt the weed seed bank community (Liebman & Davis, 2000; Hatcher & Melander, 2003). According to Teasdale et al. (2004), the introduction of specific crops, i.e. *Triticum* spp. (wheat), *Trifolium pratense* (red clover) and *Dactylis glomerata* L. (orchardgrass) in an organic spring crop rotation (*Zea mays* spp. (maize) and/or *Glycine max* (soyabean)) tends to decrease the weed seed bank and the abundance of annual broadleaf weed species. The introduction of forage legumes (Bellinder et al., 2003) reduces the weed seed bank partly through competition with weeds, but also by mowing and grazing (Liebman & Davis, 2000). In conservation tillage, seed predation is increased (El Titi, 2003) and soil disturbance responsible for weed seed germination is decreased, both leading to less weed seed return to the soil and in the long term a depleted weed seed bank. For instance, Younie et al. (2002) have demonstrated that increasing the proportion of grass/clover ley in an organic crop rotation can limit weed seed number.

**Agronomic practices.** In organic farming, intercropping and undersowing systems are recommended to avoid bare soils and to limit erosion (IFOAM, 2002). Both systems represent another option to control weeds especially with no tillage where direct mechanical weed control is hampered by crop residues at the soil surface (Bärberi & Cascio, 2001; Bond & Grundy, 2001). Several reviews on cover crops (Lu et al., 2000; Bärberi, 2002; Hartwig & Ammon, 2002; Bhowmik & Inderjit, 2003) demonstrate that weed development is controlled by competition for light, nutrients and habitat (ecological niches), and also by allelopathic effects of cover crops. However, undersown cover crops can compete with the main crop for resources.

In conventional agriculture, herbicides are used to manage the development of cover crops (Locke et al., 2002). In organic farming, cover crops can be killed by frost or by mechanical methods. Several mechanical control methods are used: (i) mowing; (ii) undercutting (Liebman & Davis, 2000; Bond et al., 2002; Hartwig & Ammon, 2002; Bhowmik & Inderjit, 2003) demonstrate that weed development is controlled by competition for light, nutrients and habitat (ecological niches), and also by allelopathic effects of cover crops. However, undersown cover crops can compete with the main crop for resources.

### Table 4 Effectiveness of mechanical weed control and conservation tillage

<table>
<thead>
<tr>
<th>Machinery</th>
<th>Effectiveness&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Suitability for different types of conservation tillage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harrowing or ‘blind harrowing’</td>
<td>For cereal crops, used few days after crop sowing. Can delay crop emergence. Effect depends on interaction between weed species emergence, timing of application (autumn, spring) and soil moisture.</td>
<td>Shallow tillage (if few or no residues on soil surface)</td>
</tr>
<tr>
<td>Hoeing</td>
<td>Better for large seeded, deeply sown crop, can be used in wet conditions and stony soils. Aggressive for soil structure.</td>
<td></td>
</tr>
<tr>
<td>Brush weeding</td>
<td>More effective for horticultural use, vegetable crop. Can be used in wet conditions, working depth is a key factor of effectiveness. Less effective than traditional hoeing for perennial grass.</td>
<td></td>
</tr>
<tr>
<td>Finger weeding</td>
<td>Good for small weed seedlings, less effective against grass weeds, little effect on established weeds. Dry soil and weather better for good weed kill.</td>
<td></td>
</tr>
<tr>
<td>Mowing, cutting and strimming</td>
<td>Cutters: weeds need to be taller than crop. Mowers: Effective for perennial broad-leaved weeds as <em>Cirsium arvense</em>, <em>Cirsium vulgare</em> (over 3 years) - Timing, frequency and cutting is critical. Strimmers: cut down seedling and larger weeds.</td>
<td>All types of conservation tillage (including no tillage)</td>
</tr>
<tr>
<td>Flaming</td>
<td>High machine cost: not justified in arable crops, effective on horticultural use. Not suitable for crops with shallow or sensitive root system. When the soil is too moist for mechanical weeding.</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>From Bärberi (2002), Bond & Grundy (2001) and Hatcher & Melander (2003)
Hatcher & Melander, 2003) or (iii) rolling techniques based on mechanical lodging and cutting coulters (Figure 3a). Rolling suppresses growth of cover crops without cutting. Soon after rolling, the next crop is drilled directly into the rolled cover crop using special equipment (Figure 3b). This allows the crop to establish before the cover crop regrows. The rolling techniques appear very promising for no tillage in organic farming although no western European references to their use are available. Research is required to adapt those methods from South and North America (New farm research, Rodale Institute, 2003), and to assess their effectiveness for weed control under European conditions. Another method involves the use of living mulches to suppress weeds with minimum competition to the main crop (Hiltbrunner et al., 2004). In Europe, the WECOF project (Strategies of Weed Control in Organic Farming) (Davies et al., 2002) was carried out to study weed control in organic farming by different cultural methods.

Disease and pest control

According to Katan (2000), conventional ploughing is effective for control of soil-borne pathogens. However, the review of Sturz et al. (1997) on plant disease indicates that conservation tillage in temperate humid agriculture induces pathogen interaction and microbial antagonism. Increased biological activity under conservation tillage can lead to competition effects and to the ‘formation of disease-suppressive soils’ (Sturz et al., 1997). For example, potatoes grown in a rotation with barley and red clover under conservation tillage were less diseased than those in a shorter rotation with conventional tillage (Peters et al., 2003). This is an area for further research.

In the temperate climate of western Europe, slugs represent one of the most important crop pests (Glen & Sysmondson, 2003). In organic farming, chemical controls, such as metaldehyde and aluminium-based slug pellets, are forbidden. Thus, slug populations must be controlled by cultural and biological means. Glen & Sysmondson (2003) in their review reported that tillage systems influence slug abundance and crop damage directly by the mechanical action of tillage implements, and indirectly by modifying soil surface conditions. They found that slug number and biomass generally increased with conservation tillage compared with ploughing. Crop residues left near the surface in conservation tillage create shelter and moisture conditions favourable for slug development. On the other hand, conservation tillage tends to increase natural enemies of slugs (Glen & Sysmondson, 2003). In a review on carabid beetles (natural predators of slugs), Kromp (1999) reported that conservation tillage favours carabid beetles more than ploughing. In organic farming, more carabid beetles were observed compared with conventional systems (Kromp, 1999). Slug damage to crops can be controlled by natural field predators or by biological control (Glen & Sysmondson, 2003). In organic farming, biological control with Phasmarhabditis hermaphrodita (nematode parasite of slugs) is efficient for limiting populations of some slug species, but the cost of this method is very high (Speiser & Andermatt, 1996; Speiser et al., 2001).

Conclusions

Although it might appear important to integrate conservation tillage into organic farming systems, there are major limitations to achieving this. Although weed control without herbicide is possible, conservation tillage, and especially no tillage, tends to increase weed pressure to a critical level where crop production could be compromised. Moreover, mechanical weed control is not well adapted to conservation tillage because of crop residues on the surface. Another problem is topsoil compaction, particularly during the first year of transition from conventional to conservation tillage. The risk of compaction will be worst on weakly structured soils particularly when conditions are wet. The transition period from conventional tillage to conservation tillage tends to be particularly prone to compaction leading to impeded drainage, restricted crop emergence and poorer root
development. Another risk of conservation tillage for organic farmers is the limited availability of nitrogen. Net mineralization of SOM – the main source of nitrogen in organic farming is reduced.

Thus, we suggest a staged approach to the adoption of conservation tillage in organic farming. The first stage is to identify whether the soil and climate are suitable. Well-drained clays, calcareous soils and other stable loams favour adoption of conservation tillage. Organic farmers, just as conventional farmers, will encounter more problems on weakly structured soils containing high proportions of sand and silt, particularly in a wet climate. Conservation tillage is particularly suited to areas prone to wind erosion and to drier areas with soils of stable structure which are resistant to compaction. Any problems of compaction or other structural degradation need to be assessed and rectified before adopting conservation tillage.

Having identified suitable soil types and suitable soil structure, the next requirement is to adopt an appropriate rotation. Choice of cropping will be affected by the need to suppress weeds in the long-term and to encourage adequate mineralization, using appropriate cover crops and intercropping (Melander et al., 2005).

The tillage requirement will vary within a crop rotation (Carter, 1994). In an organic rotation, deeper tillage is likely to be required for incorporating the ley phase to provide weed incorporation and N mineralization. However, within the arable phase, shallower conservation tillage allows rapid breakdown of residues near the surface. Application of the concept of no tillage within a living mulch looks promising (Hiltbrunner et al., 2004). On soils less suited to conservation tillage where compaction below the tilled layer is a potential problem, a system of conservation tillage combined with ‘low-lift’ tine loosening of the lower topsoil (‘two-layer’ tillage) may be possible, preferably with controlled traffic systems.

However, the successful adoption of conservation tillage in organic farming is not proven and further research is required. For instance, the potential increase of porosity due to clover growth (Popadopoulos et al., 2006) and earthworm activity both in organic farming and conservation tillage needs further investigation in situations where compaction occurs. Studies focusing on soil regeneration processes of degraded soils by biological activity should also be developed. Innovative cultural techniques, such as undersowing of crops into rolled cover crops, should be explored in temperate climates.

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