Soil fertility after 10 years of conservation tillage in organic farming

Joséphine Peigné[a, *]
jpeigne@isara.fr

Jean-François Vian[a]

Vincent Payet[a]

Nicolas P.A. Saby[b]

[a]Agroecology and Environment Department, ISARA Lyon 23 rue Jean Baldassini, 69364 Lyon cedex 7, France

[b]unité Infosol, US 1106 INRA, Orléans, France

*Corresponding author.

Abstract

It has become commonplace to consider ploughing as an agricultural practice that destroys soil fertility. Organic farmers have traditionally used the plough to till their soil and control weeds. However, there is a growing interest in adopting tillage practices without ploughing to preserve long-term soil fertility and in the hope, subsequently, of increasing crop yields. The aim of this paper is to assess if conservation tillage treatments in organic farming did in fact improve long-term soil fertility, wheat rooting and yield in a long term field experiment (2004–2015). We compared the effects of conservation tillage treatments (superficial tillage – ST- with chisel at 15 cm depth and very superficial tillage – VST- at 5–7 cm depth) and conventional tillage treatments (traditional mouldboard ploughing- MP at 30 cm depth and shallow mouldboard ploughing – SMP- at 18 cm depth without skim coulter) during 10 years on a sandy loam soil in France. To assess soil fertility, physical (soil penetration resistance, visual soil profile observation), chemical (organic carbon – Corg, total nitrogen – Ntot and available phosphorus – OlsenP) and biotic (earthworms biomass, density and diversity) soil properties were measured in 2004-5 and 2015. The effect of soil fertility on wheat roots and crop growth was also measured in 2015. VST, and to a lesser extent ST, increased Corg, Ntot and OlsenP in the upper soil layer (from 0 to 15 cm) compared to ploughing treatments. On the contrary, soil compaction increased using conservation tillage treatments (VST and ST) during the 10 years of experiment, especially in the layers between 15 and 30 cm depth in comparison with ploughing treatments. This effect is not offset by an increase in earthworm abundance and activities in conservation treatments. Earthworm biomass and endogeic abundance were even higher in SMP compared to ST. Soil compaction limits roots, with less roots in depth with VST (from 12 to 30 cm and 48 to 70 cm) and ST (from 24 to 30 cm) compared to ploughing treatments. Conservation tillage treatments had positive effects on soil chemical components in the upper soil layer and contributed to the increase of wheat biomass until tillering stage. However, no wheat yield difference was found between treatments. Physical and biotic soil properties had not significantly improved after 10 years of conservation tillage. This could be due either to the insufficient duration of the experiment to foster a positive earthworm effect on soil porosity, or to the sandy soil, too sensitive to soil compaction in this organic cropping system (intensive mechanical weeding) and unfavourable for the development of the earthworm population.

Keywords: Conservation tillage; Organic farming; Soil fertility; Wheat; Roots

1 Introduction

In organic farming (OF), the plough is traditionally used to prepare soil before seeding, for weed control, to bury intermediate crops, and incorporate organic fertilisers and amendments. However, due to soil fertility problems such as poor soil structure (compaction, soil crust) and the negative impact of tillage on soil organisms, organic farmers in Europe have shown interest in adopting conservation tillage (Casagrande et al., 2015). Conservation tillage includes many practices such as tillage with tined tools at depths down to 15–20 cm, or direct seeding without prior cultivation. Whatever the conservation techniques used, the first reason to stop ploughing is to protect the soil surface from crusting and erosion by leaving crop residues and organic matter at the soil surface. More water-stable aggregates are measured in the uppermost soil layer under conservation tillage compared to ploughing (Holland, 2004; Blanco-Canqui and Lal, 2007). In addition, several studies have shown that conservation tillage increases soil carbon stock (C) as well as the quantity, activity and diversity of soil microorganisms in the upper soil layers (Cookson et al., 2008). Conservation tillage also tends to increase earthworm biomass and diversity (Pelosi et al., 2014). It preserves their habitat (burrows), especially anecic burrows, which favour water infiltration and root penetration (Soane et al., 2012). It is also used to reduce labour time, energy consumption and machinery costs (Soane et al., 2012).

The combination of conservation tillage advantages and organic farming specificities should be beneficial, as both types of agriculture aim at preserving soil fertility and increasing sustainable cultivation practices. However, to make conservation tillage a success in organic farming, many questions still remain (Peigné et al., 2007). Main difficulties regarding the use of conservation tillage in organic farming is weed management, as the plough is traditionally used to control weeds (Peigné et al., 2007). Several studies deal with weed infestation when conservation tillage are used in organic farming (Gruber and Claupein, 2009; Krauss et al., 2010; Vakali et al., 2011; Armengot et al., 2015; Peigné et al., 2014). Cooper et al. (2016) performed a meta-analysis on the effects of conservation tillage techniques in organic farming on weeds, yields and C stocks. Results on weeds show that conservation tillage increase weed incidence compared to ploughing systems by more than 50%. The statistical relationship between weed incidence and yield is less clear, even if yields decrease by 7.6% compared to deep ploughing. They state that other limiting factors, such as nutrient availability and soil structure, explain yield reduction when conservation tillage is used in OF.

Few articles clearly demonstrate the beneficial effect of combining conservation tillage and organic farming on soil fertility. According to Stockdale et al. (2002), soil fertility can be “defined as the ability of a soil to provide the conditions required for crop growth. It is a result of the physical, chemical and biological processes that act together to provide nutrients, water, aeration and stability to the plant…”. Theoretically, the combination of conservation tillage and organic farming may increase soil organic matter content in the topsoil, preserve soil biology, which should then consequently increase overall soil fertility (Peigné et al., 2007). However, questions have been raised on the effect of conservation tillage on topsoil structure; could the risk of compaction increase with conservation tillage on weakly structured soils, such as sandy soil? (Peigné et al., 2007). The transition period from conventional tillage to conservation tillage is particularly prone to compaction, which in turn impedes water drainage and gas exchange, restricts crop emergence and leads to poorer root development (Peigné et al., 2007).

Studies, focused on soil fertility under conservation tillage in OF, often focus on the soil's biotic components (Berner et al., 2008; Kuntz et al., 2013) or chemical properties (Zikeli et al., 2013; Vakali et al., 2014; Cooper et al., 2016). Regarding physical soil properties, Vakali et al. (2011) show that conservation tillage (soil loosening up to 30 cm depth) tends to preserve soil aggregate stability, however few conclusions can be drawn regarding soil compaction as the working depth of the tested treatments was similar. Crittenden et al. (2015) studied the effect of conservation tillage *versus* conventional tillage (ploughing) in OF after 4 years of experiments, on physical soil properties and organic matter content in soils. They concluded that conservation tillage in OF had a potentially beneficial effect on soil fertility. But they also showed more soil penetration resistance using conservation tillage compared to conventional tillage. Thus, (i) the effect of combining conservation tillage and organic farming on soil fertility and (ii) the effect of soil fertility on crop development (root and shoot development) are not *a priori* clear, may not necessarily be beneficial and therefore have to be studied, especially over the long term.

After 10 years of experimentation on a sandy loam soil, the objective of this paper is to assess the effects of 2 conventional (traditional and shallow ploughing) *versus* 2 conservation tillage treatments (superficial tillage at 15 cm depth and very superficial tillage at 5–7 cm depth) on soil fertility and the resulting effect on crops. In light of the literature previously mentioned, the main questions of this paper are: (1) does the combination of organic farming and conservation tillage increase nutrients and soil carbon concentrations as well as the earthworm population? (2) Does biological porosity in conservation tillage remediate soil compaction as well as or better than mechanical porosity created by ploughing? And (3) how does the modification of soil fertility under conservation tillage affect root development and crop yields?

2 Materials and methods

2.1 Experimental design

The “Thil” trial (45°49′9.44″N and 5°2′2.62″E) was set up in 2004-5 in south-eastern France. The soil is a calcareous fluvisol developing on a recent alluvium. The soil texture is composed of 53% sand, 32% silt and 15% clay which corresponds to a sandy loam soil and the pH is 8.2. Below 60 cm, soil texture isn’t spatially homogeneous due to heterogeneity in sands and gravels deposits. The climate is classified as semi-continental with Mediterranean influences; the mean annual temperature is 11.4 °C and mean annual rainfall is 825 mm. “Thil” cropping system – an irrigated system with spring crops (maize and soybean), winter wheat and legumes as cover crops – is representative of the organic stockless grain systems found in this region. The land conversion to organic farming (EU 2092/91) started in 1999. The crop rotation is based on Maize (*Zea mays* L.)- Soybean (*Glycine max L.)*- Winter wheat (*Triticum aestivum L.)* with cereal cover crops between maize and soybean and legumes cover crop between winter wheat and maize. Soybean and Maize are intensively irrigated each year (around 300 mm) while winter wheat is irrigated according to climatic conditions (from 30 mm to 100 mm). The experiment started with a maize crop in spring 2005 after 3 years of alfalfa (*Medicago sativa*, 2002–2005).

The experimental design consists in 4 tillage treatments replicated randomly 3 times. The experimental field of 1.5 ha contains 12 experimental plots, each measuring 80 × 12 m (length × width). The plots are separated by 2 m wide grass strips. All plots can be irrigated. The 4 tillage treatments were selected according to their expected effect on soil biology and soil structure: 2 ploughing treatments, *i.e.* mouldboard ploughing at 30 cm depth (MP) and shallow ploughing at 18–20 cm with no skim coulter (SMP), and 2 treatments without soil inversion, *i.e.* superficial tillage at 15 cm with a chisel plough (ST) and very superficial tillage at 5–7 cm with rotary and/or chisel tools (VST). In 2005 and 2008, direct sowing under rolled mulch was tested on VST plots (maize on rolled alfalfa in 2005 and soybean on rolled rye in 2008). The seedbed was prepared with a rotary harrow in all treatments. Weeds were mechanically destroyed by harrowing and hoeing in the row crops, and weed control was adapted to each tillage treatment (Fig. 1). Thus the number of weeding passes was adjusted according to the degree of weed infestation in each treatment. All the agricultural tools on wheat being 4 m wide, the wheel tracks were located on the same zones in 2015 as in previous years. However, as the tools used on maize and soybeans are 4.80 m wide, this, combined with harvesting operations, means that the entire area of a plot could have been suffered some compaction by the wheels over the last 10 years. Soil fertility was assessed between November 2004 and March 2005 on a 3 year alfalfa just before the beginning of the experiment (with a maize), to determine an initial point. Soil, weeds and crop measurements were performed after 10 years of experiment on a winter wheat in 2014-15 (at the end of the second crop rotation). The details of the crop management system and sampling scheme are illustrated in Fig. 1. In 2015, winter wheat was irrigated after the soil sampling period (35 mm the 30th of May, and 70 mm in June).

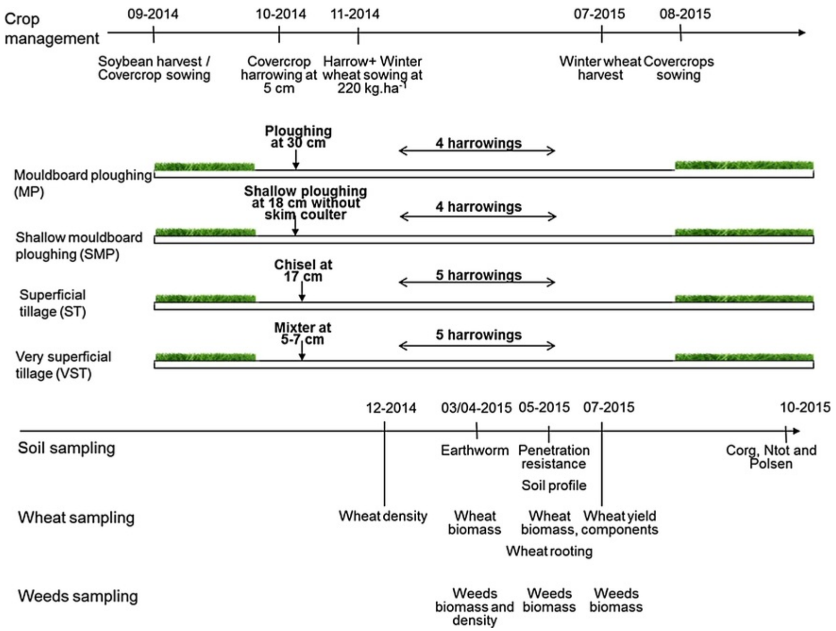

Fig. 1 Crop management and sampling dates.

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2.2 Soil fertility

2.2.1 Soil penetration resistance

The soil penetration resistance enables us to assess the state of soil structureat different depths and can be useful for understanding crop rooting. Soil penetration resistance was measured in May 2015 (Fig. 1) at wheat flowering stage. After choosing the most appropriate cone diameter (according to the compaction level), the penetrometer was pushed vertically into the soil at an approximate constant rate of 2 cm per second on each handle. Soil resistance pressure was measured every 5 cm until 50 cm depth. The recorded resistance was standardized taking into account the cross-section area of the cone; penetration resistance was expressed in MPa. Six randomly distributed measurements of soil penetration resistance were done per plot. In total, 18 replicates of soil penetration resistance measures were taken per tillage treatment (3 plots × 6 sub-replicates). Gravimetric soil water content (% mass basis) was measured on every sub-replicate at soil depths (0–5, 5–15, 15–20, 20–30 and 30–40 cm) to verify that soil moisture was similar between sampling zones. On 0–40 cm depth, soil water content is on average 15.7% (mass basis), from 17% on 0–5 cm to 12.4% on 30–40 cm soil depth.

2.2.2 Visual soil structure assessment

To understand where and why soil compaction occurs, the soil structure was characterised on a morphological basis, on the observation face of a pit (1 m deep × 3 m wide) using a methodology called ‘Soil profile’ (Roger-Estrade et al., 2004; Peigné et al., 2012; Boizard et al., 2016). On each plot of the experimental trial, two pits were dug perpendicularly to the wheel tracks of soil cultivation machinery. The macroscopic description of the face of each pit (on a vertical plane) was performed in two steps. Firstly, we located all the wheel tracks on the soil surface to indicate a lateral stratification of the soil profile. Then, soil layers delimited by the working depth of the successive tillage tools used to prepare the seedbed for the current crop were located in the soil, indicating a vertical stratification of the soil profile. The intersection of the horizontal and vertical stratification of the soil profile allowed us to define homogeneous soil compartments (Roger-Estrade et al., 2004).

Secondly, we visually assessed the structure quality of every homogeneous compartment previously defined. We classified the clods >2 cm in 3 classes according to the proportion of structural porosity visible: (1) clods with a loose structure exhibit a clearly visible structural porosity called gamma (Γ) clods; (2) clods with few biological macropores (earthworms, roots) visible on a smooth face correspond to moderately compacted clods: these are called Δb clods; and (3) clods with no visible structural porosity, evidence of severe compaction, are called delta (Δ) clods (Boizard et al., 2016). The clods have distinct physical characteristics, *i.e.* Δ clods have a higher bulk density than Γ clods, which favours anoxic conditions (Curmi, 1988) and reduces biological activity (Vian et al., 2009). To visually assess structural quality, we observed the spatial distribution of the 3 types of clod in the homogeneous soil compartments (intersection of horizontal and vertical stratification). Then, we calculated the% of area occupied by each clod type in the soil (0–30 cm depth).

Six soil profiles on the 1.5 ha trial surface were performed before the experiments began (November 2004). Soil profiles were positioned at mid-length of the plots and in the grass strips between two plots. Two soil profiles per treatment were then performed at flowering stage of winter wheat in May 2015 (Fig. 1), i.e. on only 2 plots out of the 3 having the same tillage treatments.

2.2.3 Soil organic carbon, total nitrogen and available phosphorus

Soil concentrations of organic carbon (C_{org}), total nitrogen (Ntot) and available Phosphorus (OlsenP) were measured at several soil depths corresponding to the working depth of the 4 tillage treatments (0–5 cm; 5–15 cm; 15–20 cm and 20–30 cm depth). Measurements were taken at the starting point of the experiment (2004), on a 3 year alfalfa, and in October 2015 (on a clover-grass after wheat harvest). On each plot, 12 sub-samples were randomly collected and mixed to one sample per plot (3 soil samples per tillage treatment). C_{org} was obtained by dry combustion after decarbonatation (NF ISO 10694), Ntot was obtained by the Kjeldahl method (ISO 11261:1995), and available P was measured according to the Olsen method (NF ISO 11263).

2.2.4 Earthworm biomass, abundance and density

At the beginning of the experiment, earthworm biomass was sampled with formaldehyde methods and results published in Peigné et al. (2009). As this method presents health risk and is not in accordance with organic farming principle, earthworm biomass was sampled using a hand sorting method after 2010.

Earthworm population was sampled under winter wheat in April 2015, 2 months before wheat flowering stage (Fig. 1) when earthworms are very active. Sampling was performed on 6 subplots per plot, *i.e.* 18 replicates per treatment, on a surface of 30 cm × 30 cm and to a depth of 30 cm. To sort earthworms, we used a fork-tail and worked fast enough to limit the number of anecic species which escaped as we dug to the required depth. We poured the soil in a container, and then inspected the sides and bottom of the hole to detect those earthworms ready to flee. After carefully sorting the soil collected in order to capture all the earthworms *in situ*, we placed them in a bowl filled with fine soil. Jars containing the earthworms were placed in the shade and cool and brought back to the lab. There, the earthworms were cleaned and fixed with 4% of formaldehyde, classified by ecological categories (anecic, endogeic and epigeic) and species and then counted and weighed (formaldehyde weight).

2.3 Crop performances

2.3.1 Root frequency

The interaction between soil structure and crops was measured by counting root frequency during the soil profile observations. On the face of the soil profile, soil fragments were cut off with a knife to a thickness of 1 cm to refresh the face and highlight the roots. A grid (70 cm wide and 1 m long) was attached to the face of the soil profile (Pagès, 1999; Pierret et al., 2007). The number of roots present in each cell (2 × 2 cm^2) of the grid was counted and recorded, providing an accurate indication of root frequency throughout the soil profile.

Root frequency was calculated every 2 cm, from the soil surface (2 cm depth) to 100 cm soil depth. Root frequency measured the percentage of soil occupied by roots on a soil profile face. This corresponds to the ratio of cells colonized by roots (in%) in a 2 cm deep soil layer (Pagès, 1999; Pierret et al., 2007). It is calculated by dividing the numbers of 4 cm^2 cells, where at least 1 root is counted, by the total number of cells in a soil layer of 2 cm depth (35 cells).

Root frequency was counted twice on 2 soil profiles (*i.e.* 2 sub-replicates per replicate and 2 replicates per treatment) at flowering stage of winter wheat in May 2015 (Fig. 1). The grids were located on zones in the soil profile without wheel tracks.

2.3.2 Crop growth and weed biomass

Crop growth and weed biomass were measured using the quadrat sampling method. On every plot, 16 quadrats of 0.25 m^2 were used: 8 fixed quadrats where yield components and weed density were counted (without destruction) and final grain yield was measured; 8 sampled quadrats where yield components and weed biomass were sampled at several growth stages (Fig. 1). Yield components were counted and measured at the end of winter (plant m^{-2}), flowering (wheat biomass in g m^{-2}) and harvest (Spikes m^{-2}, Number of grains m^{-2}, Kernel weight in g). Wheat yield was measured by quadrats and then extrapolated to obtain t ha^{-1} of wheat grains. Weed biomass in g m^{-2} was measured at the end of winter and wheat flowering (sampled quadrat), and at harvest (fixed quadrat) stages.

2.4 Statistical analyses

The normal distribution of each variable was verified. As the earthworm data did not follow normal distribution, a non-parametric test was performed (Kruskall Wallis test with *p*-value< 0.05). ANOVA tests were performed on the effect of the 4 treatments on: (1) weeds and wheat biomass at the end of winter and flowering stage in 2015, (2) the numbers of plants m^{-2}, (3) the numbers of spikes per plant, (4) the numbers of grains per spike, (5) thousand-kernel weight (g) and (5) wheat grain yield. In the case of statistically significant effects of treatments (*p*-value < 0.05), a multiple comparison of means was performed (Tukey test at *p*-value < 0.05).

To analyse root frequency, penetration resistance, organic carbon, total nitrogen and available phosphorus variables collected at different soil depth, two statistical analyses were performed: (1) linear regression models with autoregressive errors were adjusted to take into account the dependence of the values according to soil depth and then coefficients of the models where compared with ANOVA test, and (2) for each soil layer, classical analyses with ANOVA and multiple comparison of means were performed (Tukey test (Tukey, 1949) at *p*-value < 0.05), to understand at which soil layer values are significantly different.

Different models were adjusted according to the variables. To analyse penetration resistance, linear mixed model per treatment was adjusted with the following effects: (1) tillage treatment in interaction with soil depth modelling by a polynomial function of degree 4, as fixed effect, (2) a random effect corresponding to the replicates number, and (3) an autoregressive (order 1 covariance) structure using soil depth. To analyse root frequency, mixed model per treatment was adjusted with: (1) tillage treatment in interaction with soil depth by a polynomial function of degree 2, as fixed effect, (2) a random effect (replicates) on residual values, and (3) a correlation AR 1 in function of soil depth. For penetration resistance and root frequency variables, ANOVA tests were performed on the coefficients of the models to verify that tillage treatments in interaction with soil depth effect are significantly different.

To analyse soil concentration of organic carbon (Corg), total nitrogen (Ntot) and available Phosphorus (OlsenP), as numbers of individual values differ between 2005 and 2015, a generalised linear model per treatment was adjusted with a correlation AR 1 in function of soil depth. ANOVA tests were performed on the models to verify that tillage treatments in interaction with soil depth effect are significantly different.

To correlate soil compaction with root frequency, soil penetration resistance and root frequency data were averaged by plot. We calculated a coefficient correlation between these 2 data for all the treatments on 0–45 cm soil layer.

All the statistical analyses were performed with R software (R Core Team, 2016).

3 Results

3.1 Soil fertility

3.1.1 Soil penetration resistance

On the 0–45 cm soil layer, the models of penetration resistance of the 4 tillage treatments in interaction with soil depth effect are significantly different (*p*-value < 0.001).

From 5 to 15 cm soil depth, no statistically significant differences in penetration resistance were recorded between the 4 tillage treatments (Fig. 2). From 15 to 30 cm soil depth, significant differences were found between tillage treatments according to soil depth (Fig. 2). At 15 cm soil depth, soil penetration resistance under MP is statistically lower than VST (*p*-value < 0.05). This difference is explained by the fact that soil is not tilled in VST at 15 cm depth unlike in the other treatments. At 20 cm soil depth, soil is only tilled with MP and SMP, and soil penetration resistances are significantly lower than ST and VST (*p*-value < 0.05). At 30 cm soil depth, MP soil penetration resistance is significantly lower than the 3 other treatments (*p*-value < 0.05), as MP is the only treatment where the soil is tilled down to 30 cm soil depth. From 35 to 45 cm soil depth, no difference is found between treatments (Fig. 2).

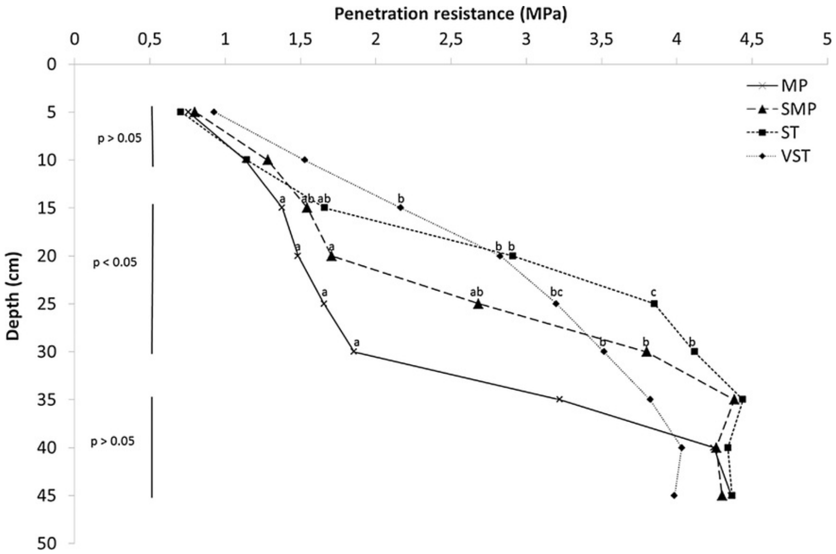

Fig. 2 Penetration resistance in MPa of the 4 tillage treatments from 5 cm to 45 cm depth in May 2015.

Eighteen individual values are used to calculate the mean. Different letters a,b means that values of treatments per soil layer with differing letter are statistically significantly different according to ANOVA test with *p*-value < 0.05, no letter means no statistically significant difference.

MP: Mouldboard ploughing; SMP: shallow mouldboard ploughing; ST: superficial tillage; VST: very superficial tillage.

alt-text: Fig. 2

3.1.2 Soil structure observation: soil profile

With only 2 replicates, no statistical analysis was performed on the results of the visual structure assessment and we only calculated mean value for each% of clods. The observations of compacted and porous zones helped to better understand soil penetration resistance results. After 10 years cultivation under different tillage treatments, total compacted zones (with and without earthworm macroporosity; Δ and Δb respectively) decreased only in ploughings treatments (MP and SMP) compared to the beginning of the experiment (Fig. 3). Indeed, only ploughing treatments (MP and SMP) increased the percentage of porous zones (Γ) compared to the initial point in 2004 (from 21% in 2004 to 39% for SMP and 52% for MP in 2015). ST and VST presented respectively 26% and 27% of porous zones in 2015, which was close to the 21% recorded in 2004.

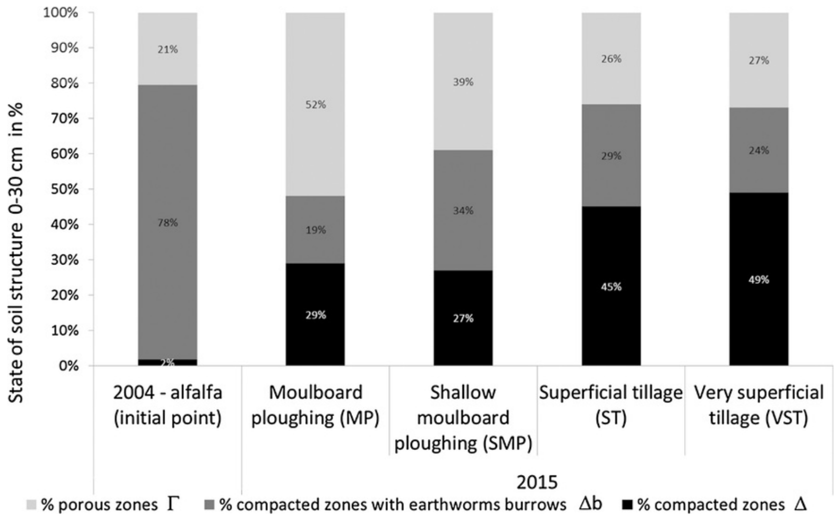

Fig. 3 Percentage of porous zones (Γ), compacted zones with earthworm burrows (Δb) and compacted zones (Δ) of the 4 tillage treatments observed in May 2015 and at the beginning of the experiment (November 2004) in a soil profile (0–30 cm depth–3 m long).

Two individual values are used to calculate the mean.

MP: Mouldboard ploughing; SMP: Shallow mouldboard ploughing; ST: superficial tillage; VSP: very superficial tillage.

alt-text: Fig. 3

Fig. 3 shows that even if MP and SMP decreased total soil compaction (Δb + Δ), severe compaction without macroporosity (Δ) tended to increase in all treatments compared to the initial point, with 21%, 27%, 45% and 49% respectively for MP, SMP, ST and VST compared to the 2% recorded in 2004.

3.1.3 Soil organic carbon, total nitrogen and available phosphorus

On 0–30 cm soil layer, the models of Corg, Ntot and OlsenP of the 4 tillage treatments and 2005-initial point in interaction with soil depth effect are significantly different (p-value < 0.001).

Corg concentration in the 0–5 cm soil layer only remained stable from 2005 (after 3 years of alfalfa) to 2015 in the VST treatment (Fig. 4a, p-value <0.05), whereas it significantly decreased in ST, SMP and MP treatments (Fig. 4a, p-value < 0.05). Corg concentration in the 0–5 cm soil layer in 2015 was significantly higher in VST treatment than in the others. In the 5–15 cm soil layer, Corg concentration in VST was significantly higher than ploughing treatments (MP and SMP) and increased significantly from 2005 to 2015 (Fig. 4a, p-value < 0.05). In the 15–20 cm soil layer, no significant statistical difference was found between the 4 treatments and the Corg concentration in this layer remained stable throughout the period 2005–2015. In the 20–30 cm soil layer, ST had a lower Corg concentration than SMP (Fig. 4a, p-value < 0.05). We could clearly observe the Corg concentration stratification in the VST treatment, with higher Corg concentrations in the soil layers from 0 to 15 cm depth compared to soil layers from 15 to 30 cm depth (Fig. 4a, p-value < 0.05). This effect was less clear with ST (main difference between 0 and 5 cm compared to 20–30 cm depth). Ploughing treatments (MP and SMP) homogenised the Corg between the soil layers.

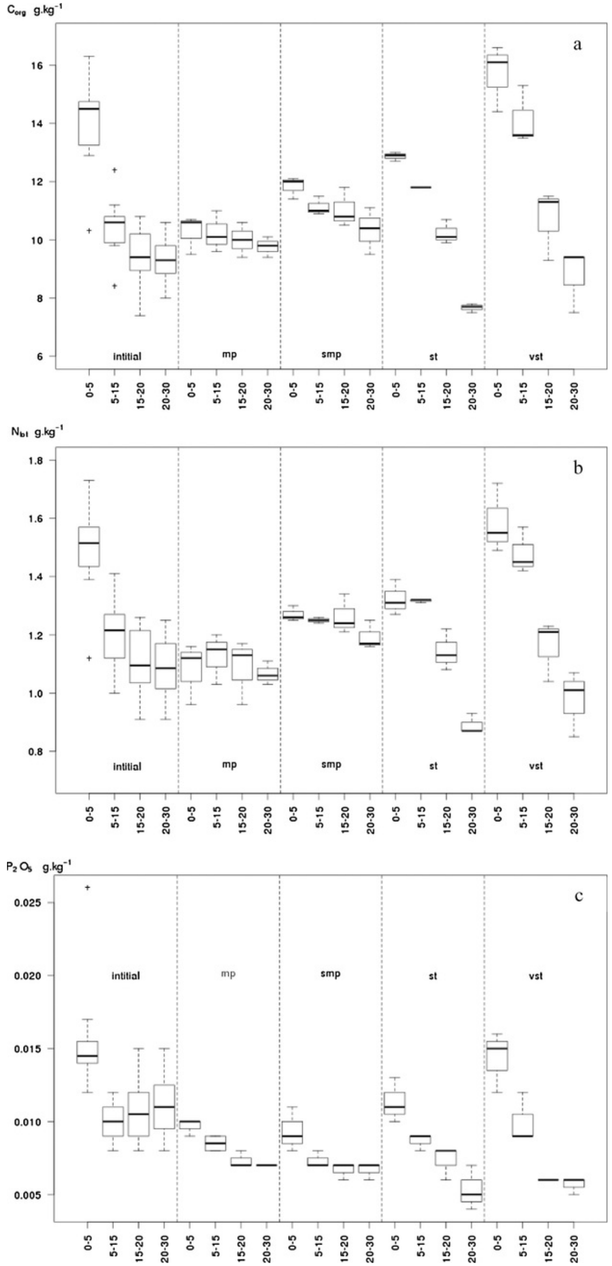

Fig. 4 a-b-c: a -Organic Carbon (Corg) in g kg^{-1}, b-Total Nitrogen (Ntot) in g kg^{-1} and c-available Phosphorus (Olsen P) in mg kg^{-1} at the beginning of the experiment (2005-initial point) and of the 4 tillage treatments from 0 cm to 30 cm depth in October 2015.

For each variable, 12 individual values are used to calculate the mean in 2005 and 3 individual values are used in 2015.

MP: Mouldboard ploughing; SMP: Shallow mouldboard ploughing; ST: superficial tillage; VST: very superficial tillage.

alt-text: Fig. 4

Fig. 4b and c shows Ntot and OlsenP concentrations in 2005 and 2015 in different soil layers. We found the same tendencies as with Corg; *i.e.* a strong Ntot and OlsenP stratification with conservation tillage treatments, especially in the VST treatment, compared to ploughing treatments. OlsenP soil concentrations after 10 years of experiment were very low. This was due to an increase of the soil pH from 8.2 at the beginning of the experiment to 8.5 (in all the treatments, data not shown) and no additional P input during the experiment. High pH value could be due to many years of irrigation in the very calcareous soil. No additional P input was a choice at the beginning of the experiment to observe P evolution in organic farming where P resource is rare.

3.1.4 Earthworm biomass, abundance and diversity

Eleven species have been identified: one epigeic species; four anecic species with one red head and three black heads, and six endogeic species (Table 1). Results differed only in the case of two species according to tillage treatments (Table 1). More *Aporrectodea nocturna* biomass was measured in SMP compared to all the other treatments (Kruskall Wallis *p*-values = 0.038). More *Allolobophora icterica* biomass and, more significantly, abundance were measured in SMP compared to ST (Kruskall Wallis *p*-values = 0.07 and = 0.0289 respectively). The principal finding was that SMP presented more total earthworm biomass (Table 1, Kruskal wallis *p*-value = 0.01299) than ST, due to greater anecic and endogeic biomasses (Kruskall Wallis *p*-values = 0.02 and = 0.047 respectively). In terms of abundance, the only significant difference observed was for the density of endogeic earthworms, with again more individuals in SMP compared to the other treatments (Kruskal wallis *p*-value = 0.04879).

Table 1 Earthworms diversity, biomass, and abundance in April 2015.

alt-text: Table 1

Ecological catego-ries	Species	Mouldboard Ploughing (MP)		Shallow Mouldboard Ploughing (SMP)		Superficial Tillage (ST)		Very Superficial Tillage (VST)	
		Ind m^{-2}	g m^{-2}	Ind m^{-2}	g m^{-2}	Ind m^{-2}	g m^{-2}	Ind m^{-2}	g m^{-2}
Epigeic	*Lumbricus castaneus*	0.9	0.3	0.9	0.2	0.9	0.3	1.8	1
	Total	0.9	0.3	0.9	0.2	0.9	0.3	2.8	1.1
Anecic red head	*Lumbricus terrestris*	1.8	9.7	3,7	8.6	0	0	0	0
	Total	3.7	10.7	3.7	8.6	4.6	2.3	0.9	0.8
Anecic black head	*Aporrectodea giardi*	0.9	2.1	4.6	6.8	1.8	3.3	11.1	11.1
	Aporrectodea longa ripicola	3.7	5.8	5.5	8.4	12.8	10.1	3.7	6.7
	Aporrectodea nocturna	9.2(a)	7.7(a)	24(a)	29.3(b)	8.3(a)	8.7(a)	16.7(a)	13.7(ab)
	Total	15.6(a)	16.9(a)	34.2(a)	44.5(b)	23(a)	22.1(a)	31.4(a)	31.4(ab)
Anecic	Total	19.3(a)	27.6(a)	37.8(a)	53.1(b)	27.6(a)	24.4(a)	32.3(a)	32.3(a)
Endogeic	*Allolobophora antipaï antipaï*	0	0	0.9	0.1	0	0	1.8	0.1
	Allolobophora chlorotica chlorotica albinica	0.9	0.3	1.8	0.3	0	0	0.9	0.1
	Allolobophora chlorotica chlorotica paratypica	0	0	0.9	0.2	0	0	0.9	0.2
	Allolobophora cupulifera	2.8	0.2	0.9	0.1	1.8	0.3	0	0
	Allolobophora icterica	25.8(ab)	10.8(ab)	50.9(a)	16.8(b)	14.7(b)	5.3(a)	23.9(b)	10.8(ab)
	Aporrectodea caliginosa caliginosa typica	16.6	5.8	18.3	5.4	22.2	6.1	28.6	10.6
	Total	46.2 (a)	11.8(ab)	74.1(b)	18.4(b)	38.9(a)	6.1(a)	61.2(a)	12.5(ab)
Total earthworms		66.3(a)	39.6(ab)	112.8(a)	71.7(a)	67.4(a)	30.7(b)	96.2(a)	45.8(ab)

For each variable, 18 individual values are used to calculate the mean. Values of treatments with different letter are statistically significantly different (Kruskall Wallis test with p-value < 0.05), no letter means no statistically significant difference.

MP = Mouldboard ploughing, SMP = Shallow mouldboard ploughing, ST = superficial tillage and VST = very superficial tillage.

Abundance of earthworms in an ecological group could be different to the sums of the individual species as unknown earthworms at specie level were attributed to the corresponding group.

No significant differences in terms of total anecic and epigeic abundances and total epigeic biomass were found in 2015 between the treatments.

3.2 Crop performances

3.2.1 Root frequency

On the 0–90 cm soil layer, the models of root frequency of the 4 tillage treatments in interaction with soil depth effect are significantly different (p-value < 0.001).

There were less roots in MP compared to the other treatments in the first 6 cm of soil (Fig. 5, p-value < 0.05). From 6 to 12 cm soil depth, there was no difference between treatments, with more than 95% of the cells colonized by roots. From 12 cm to 24 cm soil depth, there were less roots in VST than in the other treatments (Fig. 5, p-value < 0.05), and from 20 to 30 cm soil depth VST and ST presented less roots than the 2 ploughing treatments (Fig. 5, p-value < 0.05).

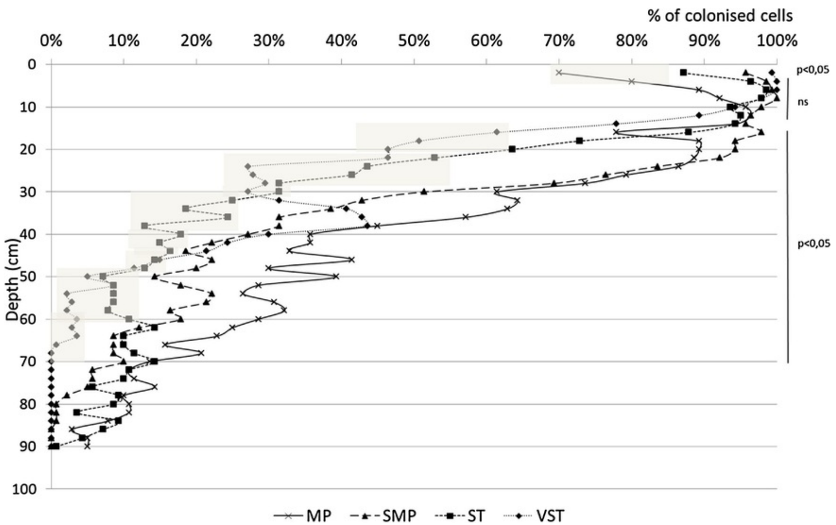

Fig. 5 Percentage of grid cells with winter wheat roots relative to the whole soil profile in the 4 tillage treatments in May 2015.

Highlighted curve segments in grey show treatment(s) which is/are significantly lower than the other treatments per soil layer (ANOVA and Tukey tests with p-values < 0.05).

Four individual values are used to calculate the mean.

MP: Mouldboard ploughing; SMP: Shallow mouldboard ploughing; ST: superficial tillage; VST: very superficial tillage.

alt-text: Fig. 5

From 30 to 48 cm soil depth, ST presented significantly less roots than the 3 other treatments (Fig. 5, p-value < 0.05). From 48 to 60 cm depth higher root frequencies were found for MP and SMP than ST and VST (Fig. 5, p-value < 0.05). From 60 to 78 cm depth, there is a transition, with less significant difference between ST, SMP and MP, but still a significant difference between VST and MP (Fig. 5, p-value < 0.05). The rooting stopped at 90 cm depth in ST, SMP and MP treatments and at 70 cm depth in VST. However, the stop of the rooting is due to the presence of gravel and sand for the 4 treatments (spatial variation of the subsoil in the field).

3.2.2 Winter wheat yield and weed biomasses

Weed biomasses were significantly higher in ST and VST, *i.e.* 0.255 and 0.246 t ha^{-1} of dry matter respectively, compared to MP and SMP, *i.e.* 0.014 and 0.027 t ha^{-1} of dry matter respectively at wheat flowering (Table 2). Same difference between treatments was found at the end of winter (Table 2).

Table 2 Weeds biomass, wheat biomasses and yield components at end of winter, flowering and harvest stages in 2015.

alt-text: Table 2

	Mouldboard Ploughing (MP)	Shallow Mouldboard Ploughing (SMP)	Superficial Tillage (ST)	Very Superficial Tillage (VST)
Weeds biomass (DM) at wheat flowering stage in t ha^{-1}	0.014 (0.007) a	0.027 (0.054) a	0.255 (0.243) b	0.246 (0.158) b
Wheat biomass (DM) at the end of winter in t ha^{-1}	0.18 (0.03) a	0.19 (0.04) a	0.25 (0.04) b	0.29 (0.08) b
Wheat biomass (DM) at flowering stage in t ha^{-1}	4.9 (0.6) a	5.4 (0.8) a	4.9 (0.8) a	5.2 (0.7) a
Number of wheat plants m^{-2} (harvest stage)	369.7 (53.4) a	391.4 (56.4) a	412.5 (53.0) a	404.7 (52.3) a
Numbers of spikes per plants (harvest stage)	1.14 (0.29) a	1.06 (0.17) a	0.97 (0.19) a	1.05 (0.18) a
Numbers of grain per spike (harvest stage)	35.5 (3.4) a	36.4 (2.1) a	34.6 (3.0) a	35.5 (3.1) a
Kernel weight (in g DM) (harvest stage)	32.4 (1.1) a	32.6 (1.3) a	32.2 (1.2) a	32.4 (1.4) a
Calculated wheat yield in t ha^{-1} (DM)	4.7 (0.75) a	4.8 (0.4) a	4.4 (0.6) a	4.8 (0.8) a

For each variable, 24 individual values are used to calculate the mean. Standard errors of the means are in parentheses. In each row, values of treatments with different letter are statistically significantly different (ANOVA and Tukey tests with p-values < 0.05).

MP: Mouldboard ploughing; SMP: Shallow mouldboard ploughing; ST: superficial tillage; VST: very superficial tillage.

DM: Dry matter.

The main significant difference in wheat growth between treatments was recorded at the beginning of the crop cycle, with more wheat biomass in t ha^{-1} of dry matter in ST and VST (0.25 and 0.29 t ha^{-1} respectively) compared to MP and SMP (0.18 and 0.19 t ha^{-1} respectively). There was no statistical difference in wheat biomass at flowering stage, regarding all the yield components and the calculated wheat yield (Table 2).

4 Discussion

4.1 Does the combination of organic farming and conservation tillage increase nutrients and carbon concentration as well as the earthworm population?

The soil organic carbon stratification in the soil profile we observed in superficial and very superficial tillage treatments was in accordance with the majority of studies (Gadermaier et al., 2011; Soane et al., 2012; Zikeli et al., 2013). This study has confirmed the importance of taking the 0–30 cm soil layer into consideration when comparing conservation agriculture treatments with ploughing regimes as pointed out by the meta-analysis of Angers and Eriksen-Hamel (2008) or those of Luo et al. (2010) and Virto et al. (2012). As pointed out by Powlson et al. (2014) the apparent increase in soil organic carbon concentration using conservation tillage treatments was mainly due to the modification of its spatial repartition in the soil. Only very superficial tillage maintained Corg concentration at soil surface at the same level as at the beginning of the experiment (after 3 years of alfalfa). The 3 other tillage treatments reduced Corg concentration at soil surface. This Corg increase at soil surface can prevent crusting on sandy loam soil. On the contrary, Corg at soil surface measured under traditional mouldboard ploughing and shallow mouldboard ploughing in 2015 was 27% and 17% lower respectively than in 2005. But Corg concentration was homogeneous in the 0–30 cm soil layer and even higher in the deeper soil layers (20–30 cm depth) than in conservation tillage treatments. These results confirmed previous studies (Angers and Eriksen-Hamel, 2008; Luo et al., 2011; Virto et al., 2012; Dimassi et al., 2013).

According to many authors, conservation tillage improves earthworm biomass and abundance, and, more broadly, biological soil properties in general (Holland, 2004; Soane et al., 2012; Pelosi et al., 2014). Even in organic farming, studies have demonstrated that earthworm biomass and diversity are greater in conservation tillage treatments such as no tillage (Peigné et al., 2009) or reduced tillage (Krauss et al., 2010). However, these results are not consistent across studies and years. Pelosi et al. (2016) showed that even though earthworm biomass tended to increase and taxonomic and functional diversity in conservation tillage treatments tended to be higher than in conventional tillage (ploughing) after 5–6 years of experiment, no clear continuous increase of diversity was found after that time. In our “Thil” experiment, previous studies concluded that earthworm density, biomass and diversity were all higher in conservation tillage treatments (Peigné et al., 2009; Pelosi et al., 2014). After 10 years of experiment, the results had evolved. Greater earthworm biomass was found in shallow mouldboard ploughing compared to traditional ploughing at 30 cm depth but also when compared to conservation tillage (superficial tillage and very superficial tillage). These results were quite surprising, but could not be put down to specific climatic or agronomic conditions in 2015 as results in 2011 and 2013 (data not shown) presented the same tendency. One hypothesis to explain this could be the use of a new sampling method, *i.e.* hand sorting instead of the formaldehyde method. According to Singh et al. (2015), a hand sorting method tends to favour the collect of endogeic and juvenile anecic earthworms whereas the formaldehyde method tends to favour the collect of big adult anecic earthworms. Several authors showed that ploughing can favour endogeic earthworms as they are less impacted by habitat destruction than anecic species and reap the benefit of the organic matter buried with the plough (Pelosi et al., 2014). Conversely, conservation tillage favours anecic earthworms as their habitat is not disrupted (Pelosi et al., 2014). The hand sorting method highlights the positive impacts of SMP on endogeic species (mainly *Allolobophora icterica*) compared to the data obtained with the formaldehyde method used at the beginning of the experiment. However, the hand sorting method doesn’t explain the higher numbers of anecic black head earthworms (mainly *Aporrectodea nocturna*) collected in SMP compared to MP and ST. Another explanation could be the effects of soil disturbance and soil compaction as both tend to negatively impact earthworm density and biomass (Jégou et al., 2002; Bottinelli et al., 2015). Shallow mouldboard ploughing would then offer the best compromise to preserve earthworm biomass, by disturbing the soil less than traditional ploughing does, and by compacting it less than in conservation tillage treatments, at least in this study.

4.2 Does biological porosity in conservation tillage remediate soil from compaction as well as or better than mechanical porosity created by ploughing?

Earthworm activity creates soil structure, their casts helping to form stable soil aggregates while their burrows forge macropores in the soil. In our study, we focused on macropore formation to remediate soil compaction. Earthworms' burrowing activity has been assessed using the soil profile method and the visual observation of clods. Very porous clods, called Γ, are composed of soil aggregates and high numbers of macropores with biotic and abiotic origins. Compacted clods can be divided into two kinds, one with no visible macropores (Δ) and the other with some visible macropores mainly due to earthworm burrowing (Δb). Our initial hypotheses were that on the one hand conservation tillage treatments would preserve or increase the number of Γ and Δb clods first assessed in 2004, and that on the other hand, conservation tillage treatments would present more Γ and Δb clods and thus less soil compaction than conventional tillage (traditional and shallow ploughings) on topsoil (0–30 cm) after 10 years experiment with different tillage treatments.

In 2004, after 3 years of perennial alfalfa, around 80% of the soil profile was visually assessed to be composed of Δb clods, i.e. moderate compaction with earthworm burrows. According to our first hypothesis, conservation tillage treatments would preserve this soil structure as the earthworm population would be maintained and their activities undisturbed, or less so than with ploughing. After 10 years, in all the tillage treatments, we observed an increase in the area occupied by severe compacted zones (Δ) on the soil profile (without any trace of biological activity) compared to what we had recorded before treatment differentiation began in 2004 after 3 years of alfalfa. One explanation could be the positive effect of a perennial crop such as an alfalfa on earthworm population and soil structure thanks to its crop rooting features in comparison with the annual crops cultivated after 2004. Moreover, alfalfa was only cut 3 times per year, meaning that the field was subjected to less vehicle traffic and les mechanical disturbances than with annual crops. Maize, soybean or wheat were cultivated with on average 15, 13 and 12 vehicle passes per cultivation year respectively. Another explanation could be the absence of any increase in earthworm biomass during these 10 years of experiment; in fact, we recorded a slight drop from 80 g m^{-2} in 2005 (Peigné et al., 2009) to less than 70 g m^{-2} in all the treatments considered in 2015. This low level of the earthworm population could be due to the sandy loam soil texture, unfavourable to earthworms (Lapied et al., 2009), and also to the absence of compost or fresh manure incorporated into the soil, agricultural practices that have been found to promote earthworm population development (Curry, 2004).

Concerning our second hypothesis, contrary to what we had expected to find, the increase in severely compacted zones (Δ) in the soil profile was higher in superficial and very superficial tillage treatments than in ploughing ones. This could result from the great number of mechanical passages on the plots cultivated using conservation treatments (tillage + mechanical weeding) in addition to harvest and fertilization operations. This mechanical pressure on soil in conjunction with unusually rainy conditions during 2013 and 2014 (968 mm and 1019 mm respectively compared to 670 mm in 2015) caused severe soil compaction, reinforced and aggravated by the natural characteristics of the soil (sandy loam soil), which is very sensitive to soil compaction and less prone to the shrinking-swelling effect. However, we expected earthworms to remediate severe soil compaction in conservation tillage treatments. Indeed, Capowiez et al. (2009) showed that earthworms are able to do this. They counted earthworm macropores in 30% of the compacted zones in plots with reduced tillage. However, they also showed that soil compaction remediation through earthworm activity can be more or less effective depending on the kind of soil compaction (plough pan, wheel track or compacted clods), spatial variability of the soil compaction and the earthworm species in the soil. For instance, Stovold et al. (2004) showed that Aporrectodea nocturna, the predominant anecic earthworms found in our experiment, tend to bury soil only in compaction-free zones. Ploughing treatments remediated soil compaction through soil inversion, and created more porous zones (Γ) than conservation tillage treatments. As regards the creation of macroposity, earthworms' burrowing activity in conservation tillage treatments seems to be less effective in comparison with mechanical porosity created by ploughing. However, the results obtained in 2015 for earthworm biomass and density were different from previous results found in the same experiment (Peigné et al., 2009). In 2009, we observed a slight increase in earthworm biomass and density in very superficial tillage compared to other treatments. This observation reinforces our hypothesis that adverse soil conditions affected earthworm development after 2009 and questions therefore the resistance and resilience of conservation tillage systems in weakly structured soils such as a sandy loam soil.

Our visual observations of soil structure were confirmed by quantitative measurements of soil penetration resistance, with less penetration resistance found in mouldboard ploughing (MP), followed by shallow mouldboard ploughing (SMP), superficial tillage (ST) and finally, very superficial tillage (VST). Penetration resistance increased in the non-tilled soil layers. Crittenden et al. (2015) showed the same result when comparing no tillage and ploughing in 2 organic fields after 4 years of experiment. The results of this experiment also demonstrated the importance of measuring the effect of tillage treatments on soil structure in depth. Indeed, if measurements had only been taken on the first topsoil layer (from 0 to 15 cm), no difference (Fig. 2) or the opposite result (less soil compaction with conservation tillage) would have been found (Crittenden et al., 2015). Reichert et al. (2016) propose a conceptual framework for soil structure evolution under no-till in a highly-weathered clayey soil, hypothesizing that this framework could also be applied to sandier or siltier soil, such as the one in our experiment. According to the authors, 4 phases can be described regarding the evolution of soil physical properties under no tillage: initial (1.5 years), intermediary (3.5 years), transitional (5 years) and stabilized (14 years). From the transitional to stabilized phases, soil re-aggregation occurs with less compaction in the 0–15 cm soil layer but with more soil bulk density and compactness below 15 cm (Reichert et al., 2016). They hypothesized that soil is re-aggregated by biological activity (from anthropogenic soil aggregates to biological soil aggregates), and that a dynamic equilibrium could be reached after 14 years. Results obtained in our study confirmed this evolution. In conservation tillage treatments, compared to ploughing treatments, we observed more roots and a majority of Γ clods (very porous clods) in the first 15 cm depth in soil profiles. And, on the contrary, we observed more penetration resistance, Δ and Δb clods, and fewer roots, below 15 cm soil depth. Soil structure had still not stabilized after 10 years of experiment, which could explain why we have not seen the effects of earthworms and roots on soil macroporosity in very superficial tillage on the whole soil profile, but only in the upper soil layer.

4.3 How does the modification of soil fertility under conservation tillage affect root development and crop yields?

Root exploration of the soil was in accordance with findings in a previous study on winter wheat (Qin et al., 2004), with greater root density in the first 5 cm soil layers under very superficial and superficial tillage treatments compared to ploughing treatments, and the opposite below 20 cm depth. Root growth depends on several factors in the soil such as soil strength due to soil density and its moisture content, and a continuous network of appropriately sized pores (Tracy et al., 2011). Difference in terms of soil strength, in our study, corresponded to difference in terms of soil penetration resistance as the moisture content is similar between treatments per soil layer. On the 0–45 cm soil layer, we found a coefficient of correlation of 0.665 between penetration resistance values and root frequency whatever the tillage treatments. Thus, higher penetration resistance from 15 to 40 cm in very superficial and superficial tillage treatments could decrease root growth compared to ploughing treatments. Similar results were found by Ehlers et al. (1983) for oats and Qin et al. (2004) for winter wheat. However, according to Ehlers et al. (1983) and Zhou et al. (2016) pore networks could play a major role in no tillage and thereby favoured root growth in depth precisely because no tillage did not disrupt pore networks as ploughing does. This effect played a major role in dry conditions when roots can hardly penetrate in too coherent soil matrix and prefer larges connected pores. In that case, results were therefore the opposite of our findings, with root growth increasing under no tillage compared to conventional tillage (Morell et al., 2011). As previously mentioned, we didn't find any more earthworms pores in very superficial and superficial tillage treatments as compared to ploughing treatments (see Fig. 3). Consequently, we didn't observe more roots in depth under conservation tillage treatments as we could have expected.

Crop yields were not significantly different between treatments. The main differences were found at early winter wheat growth stage with greater wheat biomasses under conservation tillage treatments. Then, at the beginning of the crop cycle, winter wheat growth was favoured by very superficial and superficial tillage treatments, but ploughing treatments compensated at the end of the crop cycle. Soil fertility stratification under conservation tillage treatments, with a better soil structure in the first soil centimetres, higher nutrient and organic matter concentrations, could explain higher wheat biomasses in the early growth stages compared to ploughing treatments. Pearson et al. (1991) conducted a 4 years study on the effects of minimum and conventional tillage treatments on winter wheat rooting. They found that during the first 3 years of experiment, reduced tillage tended to decrease root length at the beginning of the winter wheat cycle. However, in the fourth year, they measured more root length under reduced tillage than conventional tillage at the beginning of the cycle. The hypothesis they put forward is that the increase of C and water content in the upper soil layer under reduced tillage could favour rooting at this stage. We didn't measure the root length at the beginning of the wheat cycle, but better soil fertility observed in the upper soil layer in conservation tillage treatments could also lead to a better rooting at the beginning of the wheat cycle. However, at flowering stage, we measured less root density under conservation tillage treatments due to lower soil fertility in the deeper soil layers. This low root frequency at greater depth could impact water and nutrients uptake by the wheat and can explain the absence of biomass and grain yield differences between treatments at later growth stages (flowering and harvest stages).

5 Conclusion

Conservation tillage treatments stratified soil fertility, also in our experiment, with more Corg and nutrients found in the upper soil, with a better soil structure in the 0–5 cm soil layer and with a higher root density compared to ploughed soil. However, deeper in the soil, more soil compaction occurred with conservation tillage which could prevent deep rooting. Compacted soil layers were not regenerated by earthworm activities and thereby porosity generated through biological processes didn't counterbalance the decrease in porosity due to less mechanical loosening by soil tillage. Indeed, after 10 years of no ploughing, we didn't find more earthworms or greater earthworm activity under conservation tillage. In fact, we found more earthworms with shallow ploughing. Even if this modification in soil fertility didn't have an effect on the wheat yield in 2015, it is necessary to follow up our research into deep soil compaction and its impact on rooting so as not to reduce crop yield potential with conservation tillage.

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Highlights

- Conservation tillage in organic farming increase soil compaction.
- Earthworm population doesnt increase after 10 years of conservation tillage.
- Conservation tillage stratifies soil organic matter and nutrients in the topsoil.
- Roots frequency is limited by soil compaction with conservation tillage.

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