Title

Long and short term changes in crop yield and soil properties induced by the reduction of soil tillage in a long term experiment in Switzerland

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Abstract

To address the influence of soil tillage reduction on crop yield and soil properties, an experiment was set up in 1969 in the western part of Switzerland. A conventional tillage treatment with plough was compared to a minimum tillage treatment and a deep non inversion tillage treatment, converted to no till in 2007. Evolution of crop yield through time was investigated, as well as the soil properties in 2013. Mean soil properties and their stratification with depth were assessed. The results showed that, after 44 years, globally, all tillage treatments allowed to maintain similar yields in the long term. However, during the same time, soil properties have changed deeply. Soil organic carbon has decreased compared to the initial situation, in all treatments except in the minimum tillage. This treatment also allowed to reach high clay to carbon ratio in the upper layer, suggesting good soil structural quality compared to the other treatments. In contrast, this did not result in significant differences in carbon stocks between tillage treatments, probably due to low carbon inputs in all treatments. In addition, a strong stratification pattern with depth was observed for most of the nutrients in the minimum tillage treatment, while the situation was more homogeneous in the plough treatment. The adoption of no till also modified soil properties and lead to clear stratification patterns after only six years. These results showed that crop yield could globally be maintained in reduced tillage systems, while insuring high soil fertility and structural quality. The important decrease in the number of tillage interventions and intensity of disturbance induced an improvement of soil properties. Reduced tillage practices could thus be advantageously adopted to insure crop production together with soil fertility improvement in rather short time period.

Keywords

no till, carbon sequestration, stratification

1. Introduction

Since its beginning, agriculture has been, and still is, a major driver of soil degradation worldwide (Virto et al., 2015). Major issues related to soil in agricultural systems are erosion, run-off, nutrient leaching and soil fertility loss (Tilman et al., 2002). To respond to these problems, and lower labour and fuel costs, reduced tillage has been increasingly adopted, first in America and then in Europe (Derpsch et al., 2014; Hobbs et al., 2008; Holland 2004; Palm et al., 2014; Soane et al., 2012). The reduction of soil tillage can be more or less drastic, going from non inversion deep tillage to more extreme techniques such as shallow tillage, strip till or direct seeding. Reduced tillage has many beneficial effects, either directly or indirectly through the increase in surface residue often linked to this practice. It generally allows preserving soil fertility and biological activity, decreasing machine induced compaction, and reducing erosion and run-off (Holland 2004; Soane et al., 2012; Murugan et al., 2014; Palm et al., 2014). However, weed control is often more difficult in reduced tillage systems, and these systems widely rely on an increasing use of herbicide (Melander et al., 2013). Beneficial and detrimental effects of tillage reduction have thus to be balanced to improve the overall sustainability of the system.

Similar crop yield can be usually achieved in conventional ploughed and reduced tillage systems, though an initial transient decrease is often observed in no till systems. For example, Pittelkow et al. (2015ab) have shown that yield of most crops is reduced in no till systems with less than 5 years of practice compared to conventional systems, but is then equal. Varying changes of soil properties are expected with the abandonment of plough (Mazzoncini et al., 2011; Rasmussen 1999; Soane et al., 2012). A most controversial issue is the ability of untilled soils to stock organic carbon (Dimassi et al., 2014). While it has been long postulated that the reduction of tillage could allow to stock carbon in soils, it has been increasingly shown that differences in soil carbon stocks between differently tilled systems is mainly linked to the amount of carbon inputs (mainly crop residues) to the soil (Autret et al., 2016;

Virto et al., 2012) and to the method and depth of calculation of stocks (Dimassi et al., 2013; Ellert and Bettany1995) rather than to the intensity of tillage.

In any cases, all modifications induced by the reduction of tillage must be assessed on the long term, as many soil properties are changing slowly. In addition, several years are generally needed for the system to equilibrate after major changes such as plough abandonment. Long term experiments are thus best suited to study the effect of reduced tillage on soil properties. Several long term experiments on soil tillage exist in Europe, for example in the United Kingdom, France, Italy, Sweden. In the western part of Switzerland, an experiment comparing four modalities of tillage was set up by Agroscope in 1969. It included a conventional plough treatment and three reduced tillage treatments (deep non inversion tillage, shallow non inversion tillage and minimum tillage). In 2007, the deep non inversion tillage treatment was converted to no till. The objectives of this study were to investigate the effect of reduced soil tillage on (i) crop yield and its stability and (ii) the evolution of soil characteristics, and (iii) to study the effect of short term transition from deep tillage to no till on the same properties.

2. Materials and Methods

2.1 Experimental site and design

The experiment was established in 1969 by Agroscope in Changins (46°24’ N, 06°14’ E, 430 m above sea level), Switzerland. The average total annual precipitation is 999 mm and the mean temperature 10.2°C (30-year averages, 1981–2010). The soil of the experimental field is a Cambisol, divided into two parts presenting different textures, a clay (48% clay-37% silt) and a silty (25% clay-44% silt) soil.

The experiment follows a randomized complete block design with four main treatments of soil tillage. Until 2007, the following treatments were compared: (i) deep inversion tillage (conventional tillage with plough) 'PL', 20–30 cm, (ii) deep non inversion tillage 'DN', 25–30 cm, (iii) shallow non inversion tillage, 10–15 cm, (iv) minimum tillage 'MT', 5–10 cm. In 2007, the deep non inversion tillage treatment ('DN') was converted into a no till treatment 'NT' (last tillage in autumn 2006). As the third treatment was not monitored during the last soil analyses campaign, it was not included in this study. Each treatment is replicated three times on the clay soil and four times on the silty soil. The unit plot has a surface of 148 m^2.

2.2 Fertilisation and cultivation practices

The crop rotation, winter wheat - winter rapeseed - winter wheat - grain maize, is typical for the region. In 1993 and 2001, bad weather conditions in autumn prevented the seeding of winter wheat, which was replaced by spring wheat. Crop variety, sowing date, fertilisation (according to Swiss fertilisation guidelines, Sinaj et al., 2009), as well as fungicide and insecticide management (according to integrated crop protection principles; Häni et al., 1990) are identical for all treatments. By contrast, the timing of soil tillage and weed management are specific to each treatment. The same varieties were used for as long as possible over time. When a change was required, new varieties with similar precocity and varietal characteristics were selected. For winter wheat, only two different varieties (high quality for bread making varieties) have been used throughout the experiment, while nine varieties of winter rapeseed and eight varieties of grain maize have been sown (Supplementary Table S1).

Until 2007, wheat straw used to be exported, while maize and rapeseed residues were chopped and left on the field. Since 2007, residues of all crops are left on the field. Cover crops were sown before grain maize in 2000 (white mustard), 2008 (indian mustard) and 2012 (clover-mustard mixture), in all treatments.

Currently, the main tillage implements used for the different treatments are a mouldboard plough (PL), and a rototiller (MT). The no till treatment (NT) involves a direct seeder developed for experimentation purposes. A chisel plough was used in the deep non inversion tillage treatment (DN).

2.3 Data collection and soil analyses

Machine harvest was applied throughout the experiment to determine grain yield for each year in each treatment, from 1969 to 2013. Grain weight and humidity are measured at harvest and then used to compute dry grain yield in t/ha.

Soil organic carbon content was analysed sporadically since the beginning of the experiment, for the layer 0-20 cm, resulting in a series of 15 time points, including the initial state in 1969. In 2013, a full campaign of soil analyses was conducted on all treatments except the shallow non inversion tillage. Soil samples, at least eight cores with a diameter of 3 cm, were taken from three soil layers (0-5, 5-20 and 20-50 cm) after wheat harvest, in August 2013. Plant residues were removed from the soil samples and the individual samples were mixed to form a composite sample for each plot. Samples were oven-dried at 55°C during 72 h, sieved at 2 mm and analysed for the following soil properties: pH-water (pH-H_2O), cation exchange capacity (CEC), soil organic carbon (SOC), total nitrogen (N_{tot}), total (P_{tot}) and organic phosphorus (P_{org}), total potassium (K_{tot}), total magnesium (Mg_{tot}), total manganese (Mn_{tot}), total zinc (Zn_{tot}), total copper (Cu_{tot}), total iron (Fe_{tot}) and available forms (P_{NaHCO3}, K_{AA}, Mg_{AA}, Mn_{DTPA}, Zn_{DTPA}, Cu_{DTPA}, Fe_{DTPA}). All these elements were measured according to the Swiss standard methods (Agroscope, 1996), except P_{org} (Saunders and Willians, 1955) and P_{NaHCO3} (Olsen et al., 1954). Potential cation exchange capacity was measured according to Metson (1956). The carbon to nitrogen ratio C/N was obtained by dividing SOC by N_{tot}.

Bulk density was determined in one soil pit for each plot, at four different depths: 0-6 cm, 5-11 cm, 14-20 cm and 32-38 cm. Steel cylinders (radius: 5 cm, height: 6 cm, volume: 471 cm^3) were used to take intact soil cores, which were then dried for 72 h at 105°C and weighted. Humidity at sampling was about 30% for the clay soil and 19% for the silty soil.

Bulk density results from the 5-11 cm and 14-20 cm cylinders were averaged to represent the value of the 5-20 cm layer. The 0-6 cm and 32-38 cm cylinders were used to represent, respectively, the 0-5 cm and 20-50 cm layers.

2.4 Data analysis

To characterise each treatment, the number of tillage interventions was computed for each cultural year (from the harvest of the preceding crop to the harvest of the main crop) over the whole period from 1969 to 2013. As harvest and seeding operations are each year the same for all treatments they were not taken into account. In addition, the intensity of tillage operations was evaluated using the 'Soil Tillage Intensity Rating STIR' method from the RUSLE2 framework (USDA NRCS, 2012). This method attributes a value to each tillage implement, reflecting the intensity of soil perturbation. These values are then summed over the year to obtain a total STIR value for the cultural year.

The effect of tillage treatments on crop yield was tested by an analysis of variance, first for all crops and soils together, and then separately for each crop (n=3) x soil (n=2) combination.

The effect of tillage on mean rotation yield (from the first one 1969-1972 to the eleventh 2010-2013) was also assessed using analyses of variance, for both soil together. For each crop in each treatment, yield stability was assessed by computing the coefficient of variation of yield on all years as well as the mean rank of yield for each treatment (1=lowest yield, 3=highest yield).

The evolution of soil organic carbon (0-20 cm) through time was tested using a Mann-Kendall trend test (R package 'Kendall', McLeod, 2011).

Mean soil properties for the layer 0-20 cm were computed as the weighted mean of their values for the layers 0-5 cm and 5-20 cm and bulk density. Nutrient stocks were computed for each layer as the product of nutrient content, bulk density and layer depth. They were then corrected using the minimal Equivalent Soil Mass (ESM) method, as described in Lee et al.

(2009). The same minimal soil mass was used for all treatments within the same soil texture. Differences in soil properties and nutrient stocks were tested by analyses of variance, independently for each soil, followed by post hoc Tukey HSD tests (R package 'agricolae', de Mendiburu, 2014).

Clay to soil organic carbon ratio was computed for each layer in each treatment and soil, to assess soil potential stability, called 'n-potential' in Merante et al. (2017). It has been shown that complexed organic carbon associates with clay in a proportion of 1 g of carbon for 10 g of clay (Dexter et al., 2008). When all the soil carbon is complexed with clay and vice versa, the clay to carbon ratio (n-potential) is equals to 10. A value lower than 10 means that some of the carbon is present in a non complexed form, and thus at higher risk of loss than complexed carbon. In contrast, a value higher than 10 suggests that the clay is not fully complexed with carbon, and could be dispersed more easily than complexed clay. Clay to carbon ratio has also been shown to be an important determinant of soil structural quality (Johannes et al., 2017).

The transition from the old deep non inversion tillage DN to no till NT was studied through the comparison of soil properties in the 0-5 cm and in the 5-20 cm layer, using the 'stratification ratio' (soil properties at 0-5 cm divided by that at 5-20 cm) proposed by Franzluebbers (2002). Ratio close to one are expected in the plough treatment PL, as ploughing homogenises these layers, whereas higher ratios are expected in the minimum tillage MT treatment where a stratification with depth should exist. Stratification ratio in the new no till treatment is expected to lie between those of the plough and the minimum tillage treatments, as the former deep tillage treatment should have produced a pattern close to that of the plough treatment. The comparison of the differences obtained in the no till treatment with these two references should give insights into the evolution stage of soil properties. Analyses of variance were performed to look for differences between treatments (both soils together), followed by post hoc Tukey HSD tests to assess the position of the no till treatment compared to the two others.

All analyses were performed using R 3.3.3 (R Core Team, 2017).

3. Results

3.1 Intensity of tillage

Globally, the treatments differed in terms of number of soil tillage interventions (means: PL = 3.5, DN = 3.8 - NT = 0.2, MT = 1.3), as well as in terms of intensity of soil disturbance (means: PL = 124, DN = 100 - NT = 0.2, MT = 21). However, despite the 'constant' denomination of the tillage treatments, effective cultivation practices changed since the beginning of the experiment. In the most intensive treatments (conventional plough PL and deep non inversion DN), the tendency was towards a reduction of the number of interventions and tillage depth with time (Mann-Kendall trend test, $p<0.05$ for the number of interventions, $p<0.1$ for tillage intensity). By contrast, an increasing trend was observed for the minimum tillage MT treatment (Mann-Kendall trend test, $p<0.001$) due to the more systematic use of a rotary harrow or similar implements since the beginning of the nineties, while it was managed as a no till treatment in the first years of the experiment.

3.2 Crop yield

Considering the period before the introduction of no till (1969-2007), no significant differences between tillage treatments were observed for mean grain yield, when tested over all crops and soils, as well as for each crop x soil combination (Table 1 and Figure S1). Differences in yield between the two soil textures were observed ($p=0.003$), with higher yield in the clay soil compared to the silty soil (Table 1 and Figure S1). In contrast, a significant difference appeared between treatments ($p=0.008$, all crops and soils together) after the introduction of no till (2007-2013), with yield in the new no till treatment NT being globally lower than in the other tillage treatments. However only few data is available for the moment (3 years for wheat, 2 for maize and 1 for rapeseed).

Though no clear differences between treatments could be evidenced on the whole period, significant effects of treatments appeared when looking at the evolution through time, for each rotation from the first one (1970-1973) to the eleventh (2010-2013) (Supplementary Figure S2). During the first rotation, the minimum tillage MT showed a lower yield compared to the deep non inversion tillage DN, but it was then the best treatment until the nineties, when no differences between MT and the other treatments were observed anymore. Similarly, the first complete rotation after the transition to no till (2010-2013) presented significant differences between treatments, with lower values for the new no till treatment NT.

Concerning yield stability (1969-2007), PL was globally less stable than the other treatments, but the response was also dependent on the crop considered (Supplementary Figure S3). For wheat, regardless of soil texture, MT showed a higher mean rank than PL but also a higher coefficient of variation, DN being intermediate. For rapeseed, MT had a higher coefficient of variation and a lower mean rank than PL and DN. Finally, for maize, the less stable treatment was PL, while the most stable treatment was MT on the clay soil, with both higher mean rank and lower coefficient of variation.

3.3 Soil organic carbon

In 1969, the initial soil organic carbon SOC content (0-20 cm) was 28 g/kg and 15 g/kg in the clay and silty soil respectively. During the period 1969-2007, SOC content showed a significant decreasing trend with time (Mann-Kendall trend test, $p<0.05$) in all treatments, except for minimum tillage MT (Figure 1). Present values of SOC content (0-20 cm) in 2013 were 22.5 g/kg (PL), 25.2 g/kg (DN-NT) and 25.1 g/kg (MT) in the clay soil, and 12.4 g/kg

(PL), 12.8 g/kg (DN-NT) and 14.3 g/kg (MT) in the silty soil. The differences between tillage treatments were significant only in the silty soil (p=0.038).

Differences in SOC stock between tillage treatments were not significant in the clay soil for both 0-20 cm and 0-50 cm layers (Table 2). A significant difference in the silty soil for the layer 0-20 cm was observed (p=0.031), with higher stock in MT compared to PL, but this difference was not significant anymore for the 0-50 cm layer (Table 2).

The distribution of SOC with depth was clearly affected by tillage treatment. While SOC was similar in the 0-5 cm and 5-20 cm layers in PL, an accumulation of carbon in the top layer (0-5 cm) was observed in MT and NT (Figure 2A). All three treatments showed then a clear decrease in SOC content in the deepest layer (20-50 cm), which had similar values in the three treatments.

These SOC values corresponded to 'n-potential' values rather high, mostly largely over the threshold value of 10 (Figure 3). Following the stratification of SOC content with depth, these n-potential values differed between layers, and between treatments. The lowest n-potential values were observed in the topsoil in MT, where the accumulation of SOC conducted to values lying between 10 and 15 for the upper layer (0-5 cm), while they stood around 20 for the intermediate layer (5-20 cm). These values were not reached in NT for the upper layer, where n-potential stood between 15 and 20. In PL, most values exceeded 20, even for the upper layer. In all treatments, the bottom layer (20-50 cm) showed n-potential values higher than 30, due to the low values of SOC. Interestingly, the same trends were observed for both the clay and silty soils.

3.4 Other soil properties

In 2013, mean soil properties in the layer 0-20 cm were not significantly different between tillage treatments, except for P_{tot}, K_{tot}, Mg_{tot}, Cu_{tot} in the clay soil (Table 3).

Concerning nutrient stocks, the influence of treatments depended on the soil texture and the layers considered (Table 2). N_{tot} showed the same response as SOC, with differences observed only in the silty soil for the 0-20 cm layer (higher values in MT compared to PL, Table 2). In contrast, P_{tot} and K_{tot} stocks were influenced by tillage only in the clay soil, with higher values in NT compared to the other two treatments. This difference was however not significant for P_{tot} when tested on the 0-50 cm layer.

While the mean properties were relatively homogeneous between treatments, different patterns of changes of soil properties with depth could be observed. Bulk density was homogeneous between layers for PL, whereas it tended to be lower in the upper layer in MT and NT in both soils (Figure 2B). Concerning pH, a slight acidification of the topsoil was observed in MT and NT (Supplementary Table S2). Most of the nutrients (N_{tot}, P_{tot}, P_{org}, P_{NaHCO3}, K_{AA}, Mg_{AA}, Zn_{DTPA}, Fe_{DTPA}) showed similar results to SOC, with an accumulation in the top layer (0-5 cm), and a clear decrease in content with depth, for MT and NT (Figure 2C and Supplementary Table S2). By contrast, with PL, the layers 0-5 cm and 5-20 cm mostly gave similar values, higher than in the 20-50 cm layer. Interestingly, for Zn_{DTPA}, Mn_{DTPA}, Fe_{DTPA}, an 'inverse' stratification was observed in PL, with higher concentration in the 5-20 cm compared to the 0-5 cm layer. Almost no stratification could be observed for most total elements (K_{tot}, Mg_{tot}, Mn_{tot}, Zn_{tot}, Cu_{tot}, Fe_{tot}, Supplementary Table S2).

3.5 Stratification ratio

Looking more precisely at the difference between characteristics in the layers 0-5 cm and 5-20 cm, using a 'stratification ratio', allowed to better characterise the stratification with depth and the signature of each tillage treatment. A significant effect of tillage treatment on the stratification ratio was observed for 12 characteristics out of 21. The Tukey HSD tests revealed significant pairwise differences in all these cases. Non significant differences between treatments means that all three treatments showed no stratification or the same stratification pattern (for pH) (Figure 4, P1, see also Figure 2D). Among the significant cases, the relative position of the no till NT treatment compared to conventional PL and minimum tillage MT could be categorised into two main patterns. In the first one, NT showed values intermediate between PL and MT (P2). In the second one, NT showed similar values to MT, both different from PL (P3). All total nutrients, except N and P, fell in the no difference category (Figure 4, P1). All P forms (P_{tot}, P_{org}, P_{NaHCO3}), K_{AA}, Mn_{DTPA} and Zn_{DTPA} showed intermediate values for NT (P2). Bulk density, SOC, C/N, N_{tot}, Mg_{AA}, Fe_{DTPA} were in the third category (P3).

4. Discussion

4.1 Crop yield

Our results showed only few yield differences between tillage treatments throughout the experiment, though an initial decrease of yield was observed when new cropping techniques were adopted, visible for minimum tillage MT and no till NT treatments. This is in concordance with several studies which have shown that similar yields can be reached in reduced tillage and conventional tillage systems (Martinez et al., 2016; Pittelkow et al., 2015a; Soane et al., 2012). The initial yield decrease often observed at the beginning of reduced tillage is principally due to the methodology adopted for the long term experiment (Lechenet et al., 2016), the time needed for the involved persons (farmers, experimenters) to acquire the new necessary technical skills ('learning curve') and for the agrosystem to adapt (Derpsch et al., 2014; Pittelkow et al., 2015a; Vullioud and Mercier 2004 for this experiment). Indeed, transient difficulties linked to changes in soil structure, retention of residues on the surface, nitrogen availability, weed management or soil compaction may be observed in the early stages of conversion to minimum tillage or no till (Derpsch et al., 2014; Soane et al., 2012). Despite this initial yield reduction, the similar or higher yield subsequently observed with minimum tillage MT allowed to reach equivalent yields in the long term. However, these similar results were achieved with a total of 153 tillage interventions in PL against only 56 interventions in MT. The difference is even more pronounced when looking at the intensity of soil perturbation due to tillage, with a six-fold decrease in perturbation in MT, which is likely to reduce the risk of soil degradation. This led to reduced cost of tillage in MT, but to a slight increase in the number and cost of herbicide treatments, which however did not reach the gains due to the reduction of tillage (Vullioud and Mercier 2004).

Despite few available data for the moment, the new no till treatment NT, introduced in 2007, tended to show reduced yield compared to the other treatments. To minimise yield loss, the transition to no till should be accompanied by other adaptations of the cropping system, the most important being the retention of crop residues in the field, and the adoption of a diversified crop rotation (Govaerts et al., 2005; Pittelkow et al., 2015b; Verhulst et al., 2011). An appropriate use and management of nitrogen fertilisation and choice of crops are also crucial for a good implementation of no till (Pittelkow et al., 2015a). In this experiment, wheat straw used to be exported but this practice was abandoned in 2007 with the transition to no till. Cover crops were introduced in the rotation, before maize but this corresponded only to one year every four years. In addition, crop rotation was not modified following no till introduction, and remained relatively poor in terms of diversity (four year rotation with only three crops) and carbon input potential (e.g. no meadow in the rotation). Increasing fertilisation in the first years of the transition to no till is also a management adaptation often recommended to alleviate the modification of nitrogen cycle and the initial reduction of yield, though it should be adapted to the actual soil fertility and plant needs (Lundy et al., 2015; Pittelkow et al., 2015b; Soane et al., 2012). In our experiment improvements of these aspects could thus be a promising way to sustain the yield in the no till treatment.

Concerning yield stability, no clear patterns could be observed, as the stability of the different tillage treatments depended on the crop considered. Few studies have investigated the links between yield stability and tillage, but their results suggest that no till could improve yield stability for some crops (Fuhrer and Chervet 2015; Govaerts et al., 2005). In the future, stability of crop yield could turn out to be more and more important as, due to climate change, a higher variability in meteorological conditions from year to year is expected, and extreme and unexpected climatic events would occur more often (Calanca 2007). The delineation of specific crop-tillage combinations ensuring high stability could thus be a promising way for the mitigation of climate change in cropping systems.

4.2 Soil organic carbon

In 44 years, soil organic carbon in the 0-20 cm has drastically decreased in the conventional tillage treatment, while a lower and not significant decrease was observed in the minimum tillage treatment. This complies with many studies showing the negative impact of intensive soil tillage on the content of soil organic carbon, due to increased rate of decomposition (Lal 2002; Six et al., 2002). However, the 2013 mean differences between tillage treatments in soil organic content were weak, and these values were high compared to the global trend, especially in the silty soil. This shows perhaps a first tendency to an inversion of the decreasing trend, but it is not yet possible to test if the systematic return of wheat straw after harvest since 2007 is responsible for this observation.

No clear differences in carbon stock could be evidenced in this study, despite consistent tendencies towards higher values in minimum tillage. Studies about carbon sequestration linked to tillage reduction are widespread but largely contradictory. While some of them showed a potential for carbon sequestration with reduced tillage, many found no significant differences between the carbon stocks in plough versus no till soils (Cheesman et al., 2016; Luo et al., 2010; Palm et al., 2014; Soane et al., 2012; Virto et al., 2012). Many factors could explain these discrepancies. Among them, it has been shown that the amount of residues and carbon inputs to the soil have a major influence on carbon sequestration (Autret et al., 2016;

Saffih-Hdadi and Mary 2008; Virto et al., 2012; West and Post 2002). For this reason, if the reduction of tillage induced a global reduction of yield, carbon stock would likely not be increased. This yield reduction was however not present in the minimum tillage treatment, but was indeed observed for the first years of the new no till treatment. In this perspective, a higher frequency of cover crop cultivation in the rotation could beneficially increase carbon inputs. It will thus be interesting to see how the yield and the carbon stock will evolve for the next years in the new no till treatment. It will question also the management of the experiment and the need to adapt the crop rotation and the frequency of cover crop cultivation. Soil type (Wiesmeier et al., 2015) and climate (Dimassi et al., 2013) could also play a role, as they could, among others, influence the rate of residue degradation and turnover of soil organic carbon. Factors linked to methodological aspects are also known to be involved in the different outcomes concerning carbon sequestration. It has been shown that the depth of stock computation could largely change the conclusions about sequestration potential (Dimassi et al., 2013; Soane et al 2012; Wiesmeier et al., 2015), which seemed also to be the case in our study, as differences in stocks were mostly evidenced for the 0-20 cm layer. This influence of computation depth could however also arise from methodological bias (Kravchenko and Robertson, 2011). In addition, computation of nutrient stocks on an 'equivalent soil mass' basis has been shown to be crucial for a good comparison of different tillage treatment (Ellert and Bettany, 1995; Lee et al., 2009; Mikha et al., 2013). Indeed, the influence of tillage on bulk density could falsely induce differences in stocks if this factor is not considered properly. In parallel, uncertainties in the measurement of bulk density itself (e.g. due to differences in carbon content or soil humidity) could render difficult to properly assess changes in carbon stock.

The stratification of soil organic carbon with depth is another important factor which must be taken into account when analysing soil carbon data. Basing interpretation only on mean values could lead to misinterpretation of the data (Franzluebbers 2002). In addition, topsoil organic carbon is known to play a greater role for soil quality than carbon from the deeper layer, as it is directly involved in erosion prevention or water infiltration improvement (Franzluebbers 2002). Changes in SOC distribution with depth in reduced tillage systems have been widely documented (Luo et al., 2010; Martinez et al., 2016; Soane et al., 2012; Valboa et al., 2015). In our study, an increase in SOC content in the 0-5 cm layer was observed in the reduced tillage treatments (MT and NT), as well as a clear stratification with depth, whereas SOC content was homogeneous in the layer 0-20 cm in the conventional plough treatment (PL). This could lead to a better soil quality in the reduced tillage treatments. The new no till treatment showed a stratification ratio like that observed for minimum tillage, though its carbon content in the topsoil was slightly lower. Seven years of no till has thus been almost sufficient to reach the soil state which could be expected. Other studies have shown that the transition period, during which soil properties evolved, can reach up to 10 years, depending on the studied properties and on pedoclimatic conditions (Soane et al., 2012).

To allow better comparisons and interpretations, SOC content and stock should be interpreted along with the clay content of the soil. The clay to carbon ratio ('n-potential') has been shown to be a major determinant of crucial soil properties (Getahun et al., 2016; Johannes et al., 2017; Schjønning et al., 2012). An equilibrium value of 10 is expected when all the soil carbon is complexed with clay, and vice versa (Dexter et al., 2008; Merante et al., 2017). In this study, only the upper layer in the reduced tillage treatment reached values close to 10, all the other n-potential values being higher than 13. This means that, according to the threshold values proposed by Johannes et al. (2017), almost all our samples corresponded to a bad structural quality, due to low organic carbon content. This is not surprising since carbon inputs in this experiment are low, due to the lack of organic fertiliser inputs and of temporary meadows in the rotation. These high values show that some of the clay is not complexed with carbon and suggest potential for increased carbon sequestration (Merante et al., 2017).

Potential to improve durably soil carbon content and structural quality is thus high, especially in the clay soil. In the silty soil, the reduced amounts of clay limit the quantities of carbon that can be additionally fixed on a medium to long term period (Merante et al., 2017). This could be specifically underlined in this long term experiment placed on two different soils. Again, this demonstrates that the two major ways of increasing soil carbon content and stock, i.e. increasing carbon inputs and protecting the carbon already present, should be actively adopted here to improve soil quality.

4.3 Other soil properties

Concerning the other soil properties, most of them did not show important differences when mean values of the layer 0-20 cm were considered. However, as for soil organic carbon content, strong stratification patterns with depth were widely observed in the reduced tillage treatments, but not all properties showed the same pattern. Stratification ratio were mainly inferior to 2, even in the minimum tillage treatment, which is much lower than what was reported by Franzluebbers (2002) for organic C and N pools, but similar to what has been observed in other studies (Melero et al., 2012 in Spain; Zhang et al., 2015 in China). This could however be due to the choice of the layer thickness used to compute the ratio (Melero et al., 2012). Here the highest ratios (i.e. the strongest stratification) were observed for P_{NaHCO3} with values higher than 2 for minimum tillage. The 'strength' of stratification is known to change depending on the elements (Franzluebbers 2002; Melero et al., 2012), and this could reflect differences in plant recycling potential and turnover rates between elements. Ratios close to 1 (i.e. no stratification) in all treatments were generally observed for total nutrients, except for Ptot (and Ntot). This shows the high inertia of total elements when cropping and cultivation practices are modified.

Interestingly, the new no till treatment, which was introduced after 38 years of deep non inversion tillage, generally showed a marked stratification pattern already after 7 years. While still intermediate between the situation of the conventional and minimum tillage treatment for some of the properties (P_{tot}, P_{org}, P_{NaHCO3}, K_{AA}, Mn_{DTPA} and Zn_{DTPA}), this treatment was already similar to the minimum tillage treatment for some others. This confirms that the time necessary for soil properties to reach a new equilibrium after transition to no till is likely dependent on the considered properties (Soane et al., 2012).

In this study, bulk density was lower in the top layer in the reduced tillage treatments than in the conventional plough treatment, while it was similar in the other layers (in all treatments). This is in contradiction with many studies showing an increase in bulk density with the abandonment of plough (Alvarez and Steinbach 2009; Munkholm et al. 2003; Palm et al., 2014; Soane et al., 2012). However, this increase has also been shown to be only due to a transient compaction, which should disappear with time (Vogeler et al., 2009). Here the minimum tillage treatment is old enough to have overcome this initial compaction, but even the new no till treatment showed lower values than the conventional treatment. This effect is probably also linked to the accumulation of organic matter in the topsoil observed for the reduced tillage treatments. Other physical properties have been measured during the time course of this experiment. It has been shown notably that the stability of soil aggregates and the soil resistance to penetration were higher in the minimum tillage treatment compared to the conventional one (Vuilloud et al., 2006). Water storage capacity was also higher with minimum tillage whereas drainage capacity was reduced. A similar improvement of soil structure has been shown in many studies (e.g. Alvarez and Steinbach 2009; Bhardwaj et al., 2011; Getahun et al., 2016; Imaz et al., 2010), suggesting that reduction of soil tillage is a major driver to improve soil health and fertility.

4.4 Conclusions

This long term experiment comparing different soil tillage treatments have shown that, after 44 years, soil properties have clearly changed, but with almost no influence on the crop performance. Indeed, all treatments allowed maintaining similar yields in the long term. The modification of the soil properties suggested that soil quality was improved in the reduced tillage treatments. In addition, these treatments required a much lower number of tillage interventions than conventional plough treatment. Soil organic carbon content tended to decrease with time in all treatments except with minimum tillage. However, reduced tillage did not show the expected increase in carbon sequestration often pointed out among the benefits of minimum tillage or no till systems. Low carbon inputs are probably responsible for these findings. In this regard, long term experiments are of paramount importance to study processes which can take time to change and reach new equilibriums, such as soil properties.

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Table and figure legends

Table 1 Mean dry yield [t/ha] of wheat, rapeseed and maize in the different treatment, for the period before (1969-2007) and after the introduction of no till (2007-2013), in the two different soils. Differences between treatments are not significant ($p>0.05$) for any combination of crop and soil for the first period, and could not be tested for the second period (not enough data). PL: conventional tillage, DN: deep non inversion tillage, MT: minimum tillage, NT: no till.

Table 2 Nutrient stocks in 2013, in the three tillage treatments and two soils. Stocks were computed for the layers 0-20 cm and 0-50 cm. Different letters indicate significant differences between treatments within a given soil x layer combination.

Table 3 Mean nutrient concentration in 2013, in the three tillage treatments and two soils, for the layer 0-20 cm. Different letters indicate significant differences between treatments within a given soil. PL: conventional tillage, NT: no till, MT: minimum tillage.

Figure 1 Evolution with time of soil organic carbon content [g/kg], for the three tillage treatments. A. clay soil, B. silty soil. PL: conventional tillage, black dots and lines; DN-NT: deep non inversion tillage followed by no till, white dots and dashed lines; MT: minimum tillage, grey dots and lines. The diamonds and the horizontal dashed lines correspond to the initial carbon content at the beginning of the experiment. The trend lines are fitted using a locally-weighted polynomial regression as smoothing algorithm. Significant time trends according to Mann-Kendall tests are indicated by a star at the right end of the line.

Figure 2 Distribution of soil properties with depth in 2013, for the three tillage treatments. A. soil organic carbon SOC [g/kg], B. bulk density [g/cm3], C. total nitrogen N_{tot} [g/kg], D. cation exchange capacity CEC [meq/kg] . Black boxes: upper layer 0-5 cm; grey boxes: intermediate layer 5-20 cm; white boxes: bottom layer 20-50 cm. PL: conventional tillage; NT: no till; MT: minimum tillage.

Figure 3 Soil organic carbon [g/kg] as a function of clay content [g/kg] in 2013, for the three tillage treatments, the two soils and the three layers. P: conventional tillage; N: no till; M: minimum tillage. 1: upper layer 0-5 cm; 2: intermediate layer 5-20 cm; 3: bottom layer 20-50 cm. The stars represent the mean initial carbon and clay content at the beginning of the experiment (0-20 cm).

Figure 4 Position of the no till NT treatment compared to the conventional PL and minimum tillage MT treatments, in terms of stratification ratio of soil properties in 2013. P1: all three treatments showed no stratification or the same stratification pattern; P2: NT intermediate between PL and MT; P3: similar values for NT and MT, different from PL.

Figure S1 Evolution with time of grain yield [t/ha], for the three tillage treatments. A. winter wheat in the clay soil, B. winter wheat in the silty soil, C. rapeseed in the clay soil, D. rapeseed in the silty soil, E. grain maize in the clay soil, F. grain maize in the silty soil. PL: conventional tillage, black dots and lines; DN-NT: deep non inversion tillage followed by no till, white dots and dashed lines; MT: minimum tillage, grey dots and lines. The trend lines are fitted using a locally-weighted polynomial regression as smoothing algorithm.

Figure S2 Evolution with time of mean rotation yield [t/ha], for the three tillage treatments. Significant differences between treatments are indicated by black stars. PL: conventional tillage, black lines, DN: deep non inversion tillage, grey lines, MT: minimum tillage, dashed lines, NT: no till, grey lines. The grey dots represent the raw yield values.

Figure S3 Stability of grain yield for the period before the introduction of no till (1969-2007). PL: conventional tillage; DN: deep non inversion tillage; MT: minimum tillage. Lowercase letters stand for the crop, w: winter wheat; r: rapeseed; m: grain maize. Bold font is for the clay soil, italic font for the silty soil.

Table 1

Dry yield [t/ha]		1969-2007				2007-2013*			
		PL	**DN**	**MT**	***Mean***	**PL**	**NT**	**MT**	***Mean***
Wheat	**clay soil**	4.5	4.6	4.5	*4.5*	4.0	3.4	4.1	*3.8*
	silty soil	4.1	4.1	4.2	*4.1*	3.4	2.9	3.5	*3.2*
	Mean	*4.3*	*4.3*	*4.4*	*4.3*	*3.7*	*3.1*	*3.8*	*3.5*
Rapeseed	**clay soil**	2.5	2.4	2.4	*2.5*	2.7	2.1	2.2	*2.3*
	silty soil	2.2	2.3	2.1	*2.2*	2.1	1.7	1.9	*1.9*
	Mean	*2.3*	*2.4*	*2.3*	*2.3*	*2.4*	*1.9*	*2.1*	*2.1*
Maize	**clay soil**	6.0	5.9	6.3	*6.1*	8.7	6.0	7.4	*7.4*
	silty soil	5.7	5.9	6.2	*6.0*	8.0	6.8	8.7	*7.8*
	Mean	*5.9*	*5.9*	*6.2*	*6.0*	*8.3*	*6.4*	*8.1*	*7.6*

*After the transition to direct seeding in 2007: 3 years for wheat, 2 years for rapeseed and 1 year for maize

Table 2

Soil	Treatment	Depth	SOC t/ha	N_{tot} t/ha	P_{tot} t/ha	K_{tot} t/ha
clay[a]	conventional tillage PL	0-20 cm	57	7.8	2.1 b	52 b
	no till NT	0-20 cm	64	8.8	2.3 a	58 a
	minimum tillage MT	0-20 cm	63	8.4	2.1 b	50 b
	conventional tillage PL	0-50 cm	117	16.0	4.3	137 B
	no till NT	0-50 cm	120	16.8	4.3	148 A
	minimum tillage MT	0-50 cm	120	16.0	3.9	129 B
silty[b]	conventional tillage PL	0-20 cm	37 b	4.5 b	2.2	61
	no till NT	0-20 cm	39 ab	5.0 ab	2.3	60
	minimum tillage MT	0-20 cm	43 a	5.3 a	2.1	56
	conventional tillage PL	0-50 cm	70	8.9	4.9	156
	no till NT	0-50 cm	67	8.9	5.0	160
	minimum tillage MT	0-50 cm	73	9.5	4.3	155

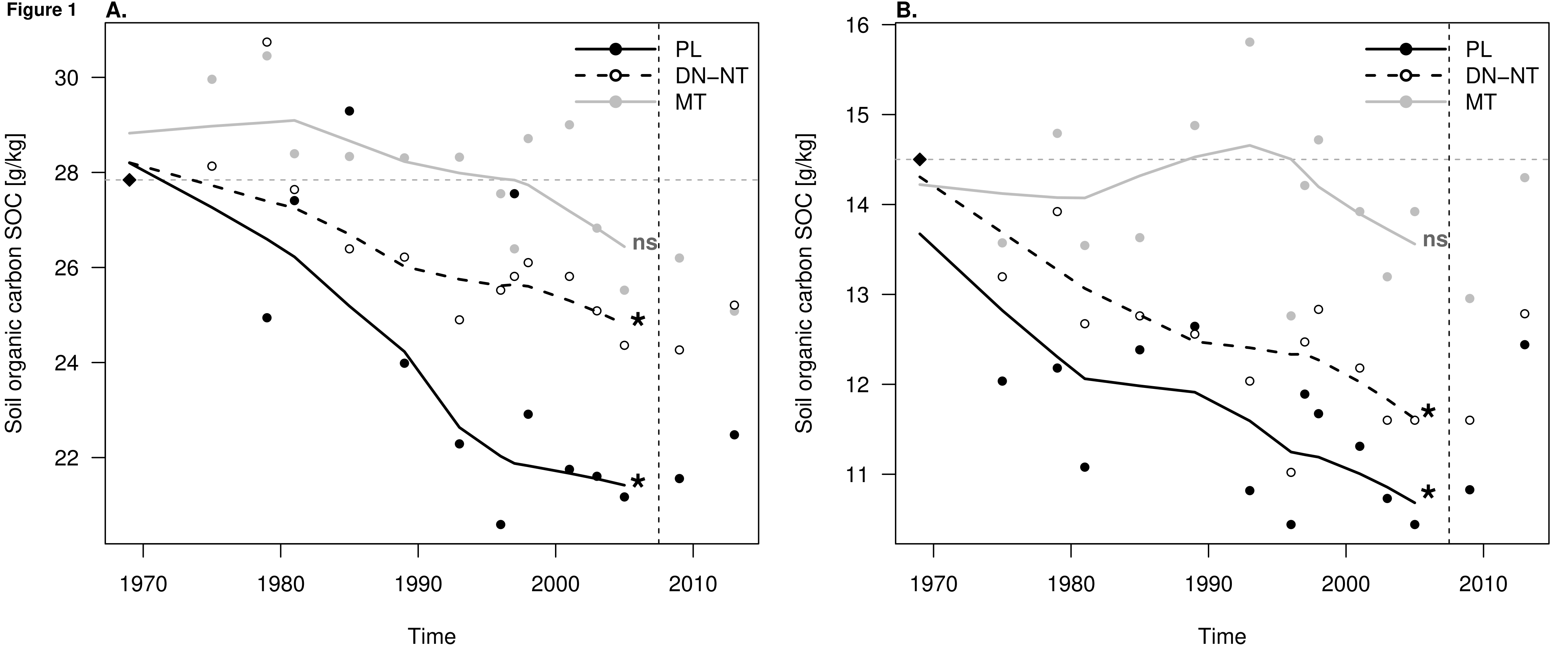
[a]equivalent soil mass is 2515 t/ha for 0-20 cm and 6645 t/ha for 0-50 cm

[b]equivalent soil mass is 3015 t/ha for 0-20 cm and 8019 t/ha for 0-50 cm

Table 3

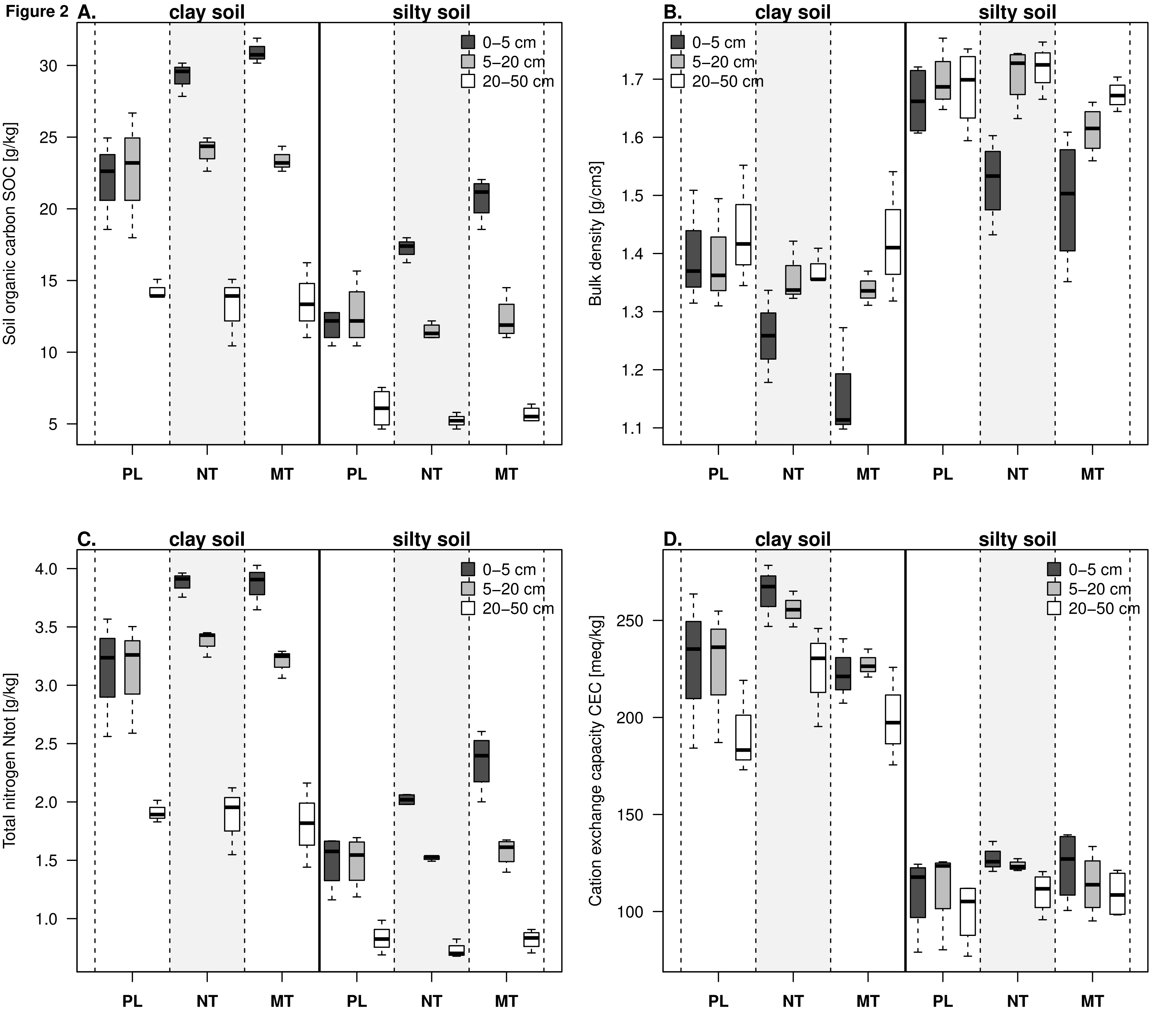
		Clay soil				Silty soil			
		PL	**NT**	**MT**	***p value***	**PL**	**NT**	**MT**	***p value***
bulk density	g/cm3	1.39	1.34	1.30	*0.438*	1.69	1.67	1.58	*0.096*
pH	H_2O	6.80	6.59	6.22	*0.068*	7.39	7.39	7.06	*0.604*
CEC	meq/kg	226	258	226	*0.328*	112	124	116	*0.394*
SOC	g/kg	22.5	25.2	25.1	*0.402*	12.4 b	12.8 ab	14.3 a	***0.038***
C/N		7.19	7.21	7.47	*0.154*	8.37	7.76	8.09	*0.232*
N_{tot}	g/kg	3.12	3.49	3.35	*0.368*	1.49	1.64	1.76	*0.058*
P_{tot}	mg/kg	838 b	919 a	841 b	***0.001***	733	760	706	*0.582*
P_{org}	mg/kg	391	440	419	*0.066*	257	279	279	*0.242*
P_{NaHCO3}	mg/kg	19.6	19.5	17.6	*0.723*	17.9	19.7	16.4	*0.201*
K_{tot}	g/kg	20.8 b	23 a	19.7 b	***0.003***	20.2	19.8	18.5	*0.141*
K_{AA}	mg/kg	217	240	203	*0.212*	168	179	175	*0.708*
Mg_{tot}	g/kg	12.0 b	14.0 a	12.0 b	***0.012***	10.3	10.3	9.6	*0.399*
Mg_{AA}	mg/kg	247	357	278	*0.135*	99	122	121	*0.251*
Mn_{tot}	g/kg	0.92	0.91	0.78	*0.334*	0.86	0.84	0.85	*0.964*
Mn_{DTPA}	mg/kg	36.4	32.1	28.5	*0.341*	21.2	23.9	19.4	*0.674*
Zn_{tot}	mg/kg	94.7	107.6	101.4	*0.106*	71.2	72.0	70.1	*0.890*
Zn_{DTPA}	mg/kg	1.58	1.72	1.58	*0.622*	0.97	1.06	1.02	*0.493*
Cu_{tot}	mg/kg	37.2 b	43.0 a	38.4 b	***0.021***	31.7	33.3	30.5	*0.602*
Cu_{DTPA}	mg/kg	3.25	4.24	3.49	*0.114*	1.96	2.11	1.93	*0.741*
Fe_{tot}	g/kg	42.4	49.4	42.1	*0.071*	33.2	33.8	31.4	*0.512*
Fe_{DTPA}	mg/kg	109	111	142	*0.148*	55	51	60	*0.700*

Figure 1



A.
PL
DN−NT
MT
ns
*
*
Soil organic carbon SOC [g/kg]
30
28
26
24
22
1970
1980
1990
2000
2010
Time
B.
PL
DN−NT
MT
ns
*
*
Soil organic carbon SOC [g/kg]
16
15
14
13
12
11
1970
1980
1990
2000
2010
Time

Figure 2



A.
clay soil
silty soil
0–5 cm
5–20 cm
20–50 cm
Soil organic carbon SOC [g/kg]
PL
NT
MT
PL
NT
MT
B.
clay soil
silty soil
0–5 cm
5–20 cm
20–50 cm
Bulk density [g/cm3]
PL
NT
MT
PL
NT
MT
C.
clay soil
silty soil
0–5 cm
5–20 cm
20–50 cm
Total nitrogen Ntot [g/kg]
PL
NT
MT
PL
NT
MT
D.
clay soil
silty soil
0–5 cm
5–20 cm
20–50 cm
Cation exchange capacity CEC [meq/kg]
PL
NT
MT
PL
NT
MT

Figure 3

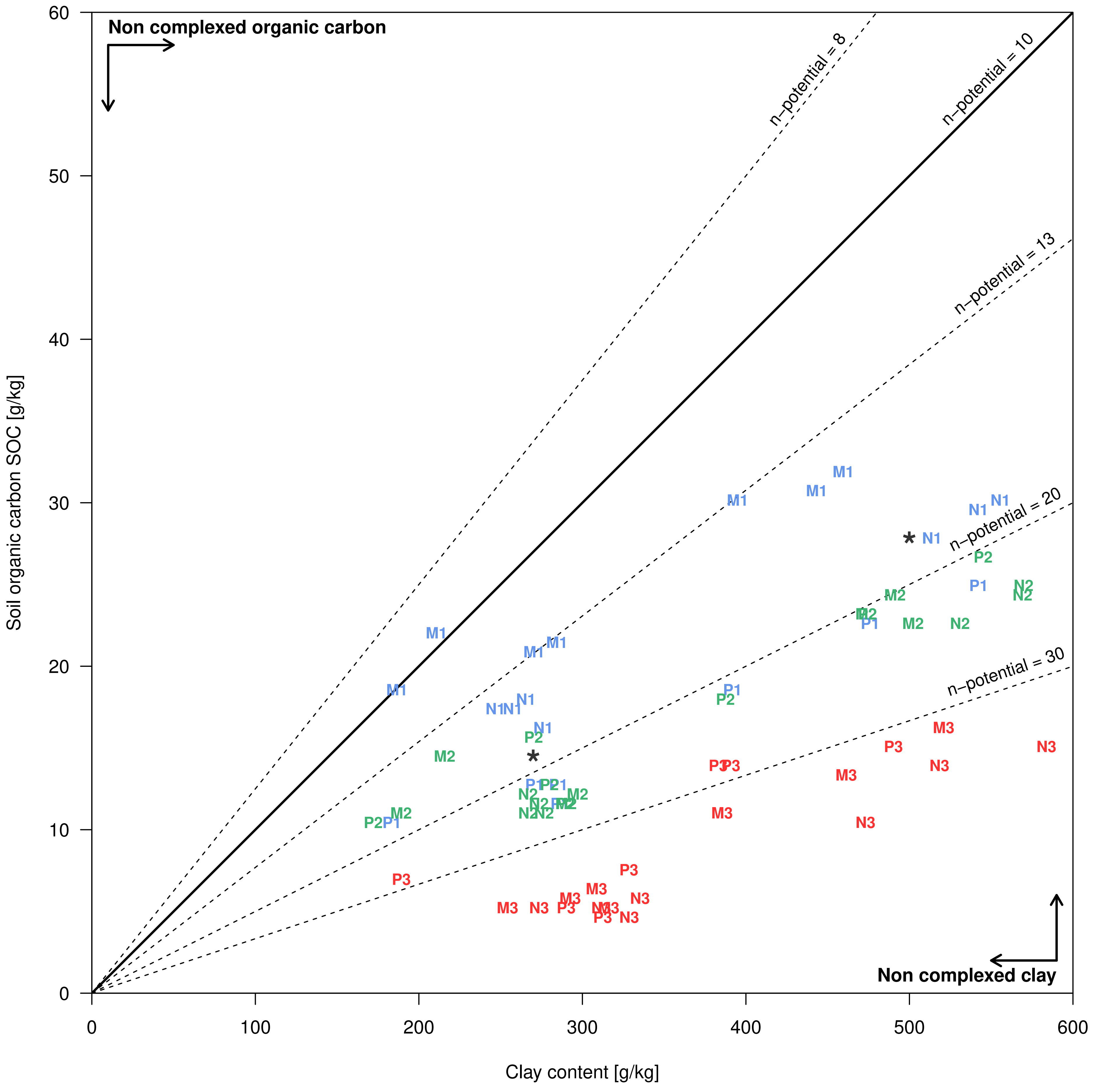
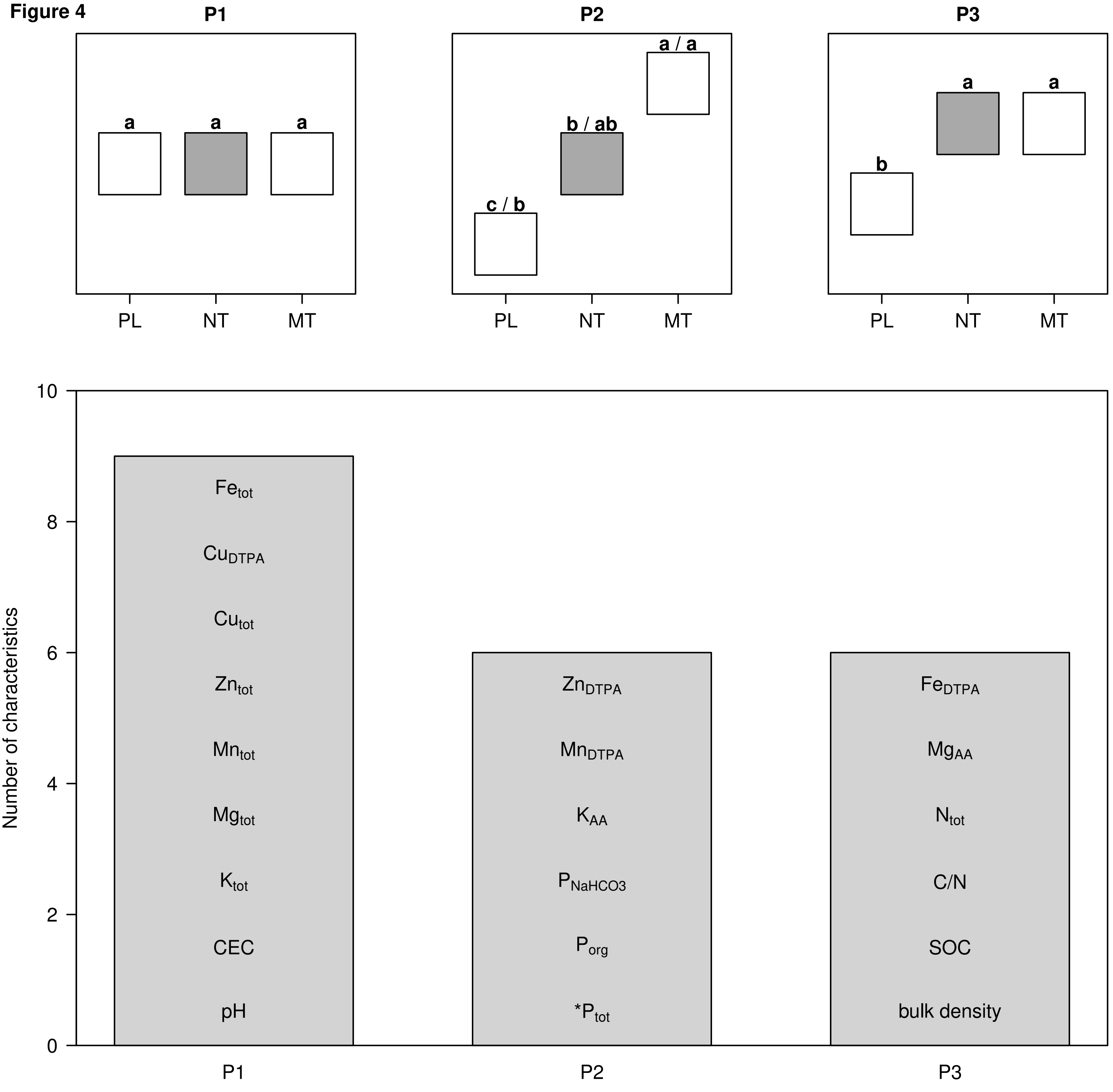

Non complexed organic carbon
Non complexed clay
n–potential = 8
n–potential = 10
n–potential = 13
n–potential = 20
n–potential = 30
Soil organic carbon SOC [g/kg]
Clay content [g/kg]
0
10
20
30
40
50
60
0
100
200
300
400
500
600
M1
N1
P1
M2
N2
P2
M3
N3
P3

Figure 4



P1
P2
P3
a
a
a
c / b
b / ab
a / a
b
a
a
PL
NT
MT
PL
NT
MT
PL
NT
MT
10
8
6
4
2
0
Number of characteristics
Fe_tot
Cu_DTPA
Cu_tot
Zn_tot
Mn_tot
Mg_tot
K_tot
CEC
pH
Zn_DTPA
Mn_DTPA
K_AA
P_NaHCO3
P_org
*P_tot
Fe_DTPA
Mg_AA
N_tot
C/N
SOC
bulk density
P1
P2
P3

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